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ROTORCRAFT WEIGHT TRENDS IN LIGHT OF STRUCTURAL MATERIAL CHARACTERISTICS

W. Z. STEPNIEWSKI
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Prepared for:

U. S. Army Aviation Systems Command
Ames Research Center
under P.O. DAAJ09-84-M-0706

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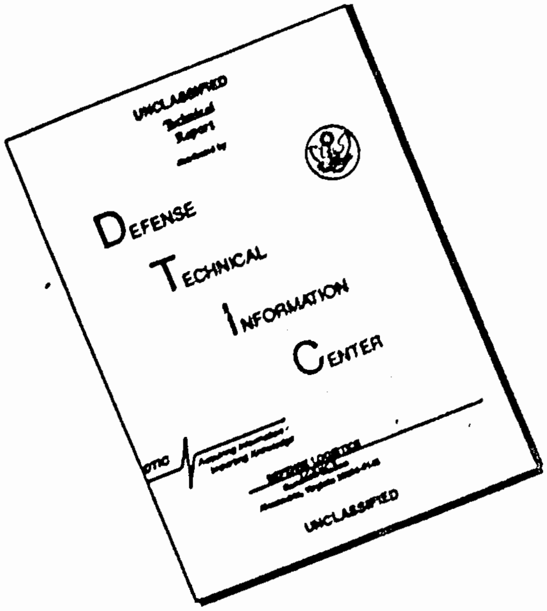

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FOREWORD

A low weight-empty to operational gross-weight ratio ($\bar{W}_e$) is an important factor contributing to a successful design of any air-transport vehicle. But this ratio is especially significant for aircraft operating in the VTO mode. In this case, one can not increase the aircraft takeoff weight by extending the ground run, as the case may be in CTO, or even STO, machines. Consequently, $\bar{W}_e$ values (based on the maximum permissible gross weight for vertical takeoff operation) is the most important factor dictating the level of useful load and as well as the payload that can be carried. No wonder that a continuous search for the lowest possible $\bar{W}_e$ values is a characteristic trademark throughout the history of rotary-wing aircraft.

In order to understand the course of this endeavor, one must realize that victory or defeat for a low relative weight empty depends on the outcome of the quest for the lowest possible relative weights of all major rotorcraft components. Going one step further in analyzing the search for a low $\bar{W}_e$, one should anticipate that strength and rigidity vs. weight characteristics of structural materials represents one of the most important factors dictating the level of relative weights of major rotorcraft components

The intent of this study is to acquaint the reader with some historic perspective of the continuous fight for low relative weight-empty of the rotorcraft as a whole, as well as for their major components. It is also intended to show how the size of aircraft – as expressed through its maximum permissible flying gross weight – could affect the relative weight levels of the components and the rotorcraft as a whole.

In an attempt to convey an indepth perspective of historic and size-related trends, current (wherever possible) as well as hypothetical Soviet helicopters are included in this study.

To assist the reader in understanding the influence of structural material characteristics on the relative weight levels of major rotorcraft components, the weight effectiveness of materials, both for static and fatigue-type loadings are reviewed. Then, cursory expressions are developed, permitting one to roughly estimate how the strength effectiveness values of structural materials could, in turn, affect the relative weights of the components. In some cases, it is also indicated that because of special constraints, possible weight reductions can not be realized in actual designs. Consequences of requirements for high moments of inertia in the case of lifting-rotor blades (entry into autorotation and coning angles) are reviewed as an example of such constraints.

In conclusion, structural materials that appear to exert the highest impact on reduction of rotorcraft component weights are briefly reviewed. In this respect, weight-effectiveness indices of materials in various loading modes are given. Operational and economic constraints which may limit the practical use of some materials in spite of their promising strength/weight characteristics are briefly discussed.

The concluding remarks at the end of this report also contain recommendations for studies along the lines indicated here.

This study was initiated by R. Shinn, formerly of AVRADCOM, St. Louis (presently, at McDonnell) who, at that time, visualized the project as a joint venture between AVRADCOM and International Technical Associates, Ltd., with Mr. Shinn being assigned as technical monitor of the project. However, following his departure from St. Louis, all technical work became the sole responsibility of ITA. Technical cognizance was eventually transferred to the U.S. Army Aviation Research and Technology Activity at Ames Research Center, with C.C. Ingalls serving as technical monitor.

Within ITA, the undersigned served as principal investigator and was assisted in the trend studies by A. Schmidt (formerly of Boeing Vertol), while Wanda L. Metz was responsible for computer inputs, as well as for the editing and composition of the text.

In the course of the project, much valuable technical material was obtained from AR&TA and the following companies: Aerospatiale, Boeing Vertol, and MBB, while the following representatives of government agencies and companies representing the aircraft industry were kind enough to contribute their personal suggestions and/or review of parts of the text: Dr. R. Carlson and Mr. C. Ingalls (AR&TA), Messrs. d'Ambra (Aerospatiale), C. Albrecht and R. McIntyre (Boeing Vertol), H. Huber (MBB), and R. Shinn (McDonnell). To all of these organizations and individuals, we wish to express our sincere thanks.

W. Z. Stepniewski

Drexel Hill, Pa. USA
April 28, 1987

CONTENTS

LIST OF SYMBOLS

a	coning angle
A	area
cpr	cycles per revolution
C	coefficient of critical length, or compression force
CF	centrifugal force
d	diameter
E	modulus of elasticity
F_{tu}	ultimate tensile allowable
FM	figure of merit
G	modulus of rigidity
h	height
I	section moment of inertia
J	blade moment of inertia
l	unit length
m	mass
M	moment
n_{cy}	number of cycles
N	number of loading cycles
P	power, or transmission rating
P_e	Euler buckling load
r	radial position
R	stress ratio, or radius
RHP	rotor horsepower
s	stress
S	surface
t	thickness
T	tensile load, or force
T_{bl}	blade tip(s)
T_{tl}	total projected life span
V	volume
w	disc loading
$\tilde{w}$	weight per unit area
W	weight
W_e	weight empty
α	mass ratio
γ_n	specific weight
δ	specific gravity
η_n	weight-effectiveness index
θ	twist
κ	parameter in drive-system weight correlation
μ	loading mode
ρ	air density
τ	load per unit length

Subscripts

al	allowable
av	average
ax	axis
b	bending, or baseline
bl	blade(s)
bu	buckling
c	compression
cyl	cylinder
des	design
ds	drive system
e	endurance
en	engine
E	buckling & linear deflection
f	fuselage
fc	flight controls
fs	fuel system
h	hubs & hinges, or hovering
lg	landing gear
max	maximum
min	minimum
n	material or component, in general
nl	no load
nm	new materials
pe	panel
pss	propulsion subsystem
s	stress
sh	shear
st	steel
t	tensile (tension), or twist
to	torsion
tot	total
tr	tail rotor
ult	ultimate
wa	water
θ	twist, torsion, deformation

Superscripts

$-$	relative
$\sim$	per unit

CHAPTER 1

TRENDS IN RELATIVE WEIGHT—EMPTY OF ROTORCRAFT AND MAJOR STRUCTURAL COMPONENTS

1.1 Introduction

Keeping the weight-empty to gross-weight ratio (referred to as relative weight-empty $\overline{W}_e$), as low as possible is one of the most important factors in creating an operationally efficient vehicle as far as load-carrying activities or time on station is concerned. Two other very significant inputs toward the goal of transportation efficiency are (1) the broadly interpreted block speed (including such aspects as turn-around-time and time required for service), and (2) fuel consumption per unit of gross weight and unit of distance traveled.

In the case of time-on-station, fuel consumption per unit of gross weight and unit of time in operation will be substituted for Items (1) and (2).

It is obvious, hence, that knowledge of statistical trends in $\overline{W}_e$ levels, as well as an understanding of all the factors influencing these trends, would be of prime interest to both system planners and designers of rotary-wing aircraft in the West, and to students of Soviet rotorcraft technology as well.

With respect to statistical trends, the two most interesting would be (a) the temporal trend, representing the variation of $\overline{W}_e$ vs. the year that the rotorcraft was placed in service, and (b) the influence of aircraft size (expressed through its maximum flying gross weight W_{max}) on the relative weight-empty level.

In determining the factors influencing $\overline{W}_e$ values, one may anticipate that strength-weight characteristics of structural materials would play an important role. It should be remembered, however, that the other two previously mentioned factors; namely, block speed and fuel consumption would also influence the $\overline{W}_e$ magnitude.

For instance, speed requirements may be instrumental in the power-installed value and hence, the engine-weight level, while fuel consumption would influence the weight of the fuel system. However, in spite of the fact that powerplant aspects represent a significant factor contributing to the $\overline{W}_e$ level, this report is exclusively devoted to the study of the influence of non-powerplant rotorcraft structures, since incorporation of the powerplant would approximately double the required effort.

It is obvious that the $\overline{W}_e$ level will, in turn, be influenced by the relative weights of its major components. Consequently, in order to obtain a better insight into the formulation of the most important relative weight-empty trends; namely, $\overline{W}_e = f(time)$ and $\overline{W}_e = f(W_{max})$, similar statistical trends will be established for Western and Soviet rotorcraft for the following major components as defined in Ref. 1.

1. Main rotor blades
2. Main rotor hub and hinges
3. Fuselage (with cowlings)
4. Landing gear
5. Drive system
6. Fuel system
7. Flight-control group

In this way, groundwork will be laid for evaluation as to the extent that potential improvements in component relative weights resulting from the application of advanced structural materials may contribute to a reduction of the relative weight-empty of a rotorcraft as a whole.

Trends in the tail-rotor group and propulsion subsystems, which are usually also classified as major rotorcraft components[1], are not examined here, as their contribution to $\bar{W}_e$ values may be considered as second-order effects. A detailed study of the fixed-equipment group, although quite important from the $\bar{W}_e$ point of view, is also not performed here, as the requirements for this group are, to a large degree, determined by the customer.

A formal definition of relative weight-empty may be based either on design (W_{des}) or maximum permissible flight (W_{max}) gross weights.

In the first case,

$$\bar{W}_{e_{des}} = W_e/W_{des} \tag{1.1}$$

and in the second,

$$\bar{W}_e = W_e/W_{max} \tag{1.1a}$$

where W_e is the weight empty.

Selection of the maximum flying gross weight as a reference basis (Eq. (1a)) should be considered as more meaningful for the establishment of comparative weight trends. This is due to the fact that design gross weight is often established somewhat arbitrarily, while the maximum permissible flying gross weight is usually more definitive in determining the actual rotorcraft operational load-carrying capability[1].

Consequently, in this study, trends in the relative rotorcraft weight-empty and relative weights of their major components will be carried out, using W_{max} as the basis for comparison.

1.2 Trends in Weight-Empty to Gross-Weight Ratios

1.2.1 General

The Sikorsky R-4, introduced into service in 1943/44, was the first production helicopter in the world. This rotorcraft, at a maximum flying gross weight of 2,540 lb, had a weight empty of 2,011 lb; thus, its weight-empty to gross-weight ratio amounted to $\overline{W}_e = 0.79$.

With respect to Soviet helicopters, the Mil Mi-1, which entered into service in 1951 – seven years after the R-4 – was their first production model. Its weight-empty to maximum gross-weight ratio was also equal to 0.79.

Through the years, values of the weight-empty to maximum gross-weight ratios descended from $\overline{W}_e = 0.79$ *(high for any aircraft)*, attaining a level in the West of $\overline{W}_e = 0.41$ (McDonnell-Douglas 500E), and 0.5 in the USSR (Mil Mi-26).

Table 1.1 was prepared in order to show in more detail the variation of the weight-empty to maximum flying gross-weight ratio occurring throughout the years, as well as the influence of rotorcraft size (expressed through maximum flying gross weight) on relative weight empty. Here, all the necessary information regarding maximum flying gross weight, weight empty, and year of introduction into service was assembled for a number of Western and Soviet rotorcraft covering the time span from 1950 to the present; even showing some projections up to 1998. The main source of data for helicopters was Janes Yearbooks from 1950/51 through 1985/86[2]. Information regarding Western hypothetical tilt rotors was obtained from Ref. 3, while inputs related to Soviet helicopters were gathered from Ref. 4, supplemented by data from Ref. 2.

1.2.2 *Temporal Variations of $\overline{W}_e$ Ratios*

Temporal variations of the weight-empty to the maximum flying weight weight ratios listed in Table 1.1 are graphically presented in Fig. 1.1. This figure illustrates how the high ratios of $\overline{W}_e = 0.79$ for the R-4 and Mi-1 have evolved through the years to the optimal level of 0.4 for Western and 0.5 for Soviet helicopters.

Looking at Fig. 1.1, one would note the following:

1. The 1950-1960 time span represents a period of rapid improvements in the $\overline{W}_e$ ratios of both Western and Soviet helicopters of all configurations. This, of course, was chiefly due to the replacement of reciprocating engines by much lighter gas turbines. From early 1960 to the present, gains in weight-empty appear much slower. The state-of-the-art progress can be judged by the so-called optimal boundaries of Soviet and Western rotorcraft.

2. Looking at the optimal boundaries, it appears that as far as the potential state-of-the-art is concerned, Western technology is still able to produce helicopters with a lower weight-empty to gross-weight ratio than their Soviet counterparts. However, when one looks at the actual points of Western and Soviet helicopters for the 1980s, it appears that the average $\overline{W}_e$ for the West would not be as

TABLE 1.1

RELATIVE WEIGHT-EMPTY ESTIMATES

DATA SHEET - WESTERN HELICOPTERS

MFGR	MODEL	YEAR	MAX FLYING WT	WT EMPTY	REL. WT	COMMENTS
Aerospatiale	SA-330J	1978	16315	8303	0.51	Also known as the Puma
Aerospatiale	SA-365N	1981	8818	4447	0.50	Also known as Dauphin 2
Aerospatiale	AS-332L	1981	18410	9402	0.51	Also known as the Super Puma
Aerospatiale	365	1983	8920	5992	0.67	
Agusta	A-109A	1976	5732	3126	0.55	Also called Mark II
Agusta/Sikorsky	AS-61N1	1984	22000	12522	0.57	Known as Silver
Bell	UH-1A	1959	7200	3860	0.54	Also known (Army) Iroquois (Bell 204)
Bell	UH-1B	1961	8500	4519	0.53	Bell Model 204
Bell	UH-1D/H	1963	9500	5210	0.55	Bell Model 205
Bell	AH-1G	1967	9500	6073	0.64	Also known as Model 209 - Huey Cobra
Bell	UH-1N	1970	11200	5822	0.52	Bell Model 212 (Canadian CH-135)
Bell	412	1981	11900	6470	0.54	
Bell	214ST	1982	17500	9651	0.55	Also known as Super Transport
Bell	XV-15	1983	15000	9570	0.64	Bell Model 301 (Army XV-15)
Bell Boeing	V-22	1990*	55000	31818	0.58	*Projected service year (STOL version)
Bell Boeing	V-22	1990	47500	31818	0.67	*Projected service year (VTOL version)
Boeing Vertol	CH-47A	1963	38550	18048	0.47	
Boeing Vertol	CH-47A	1963	33000	17913	0.54	
Boeing Vertol	CH-46A	1964	21400	12406	0.58	
Boeing Vertol	CH-46E	1966	23300	15190	0.65	Also known as Sea Knight
Boeing Vertol	CH-47B	1967	40000	19555	0.49	
Boeing Vertol	CH-46F	1968	23300	13342	0.57	
Boeing Vertol	CH-47C	1968	46000	20547	0.45	
Boeing Vertol	YCH-62A	1979	148000	64880	0.44	
Boeing Vertol	YUH-61A	1979	19700	9750	0.49	
Boeing Vertol	CH-47D	1980	50000	23162	0.46	
Boeing Vertol	234LR	1981	48500	24500	0.52	Known as Long-Range Helicopter
Eurofar	Hypo.	1998	28665	13649	0.48	Hypothetical STO
Eurofar	Hypo.	1998	22491	13649	0.61	Hypothetical VTO
McDonnell-Douglas	[illegible]	1982	3550	1441	0.41	
McDonnell-Douglas	[illegible]	1983	21000	10760	0.51	Also designated the Apache
MBB	[illegible]	1966	5114	2622	0.51	
MBB/Kawasaki	BK-117A-3	1981	7055	3737	0.53	
Piasecki	HUP-[illegible]	1951	6100	4132	0.68	
Piasecki	H-21	1951	15000	8390	0.56	
Sikorsky	H-34A	1955	13300	7630	0.57	
Sikorsky	H-37A	1955	31000	20831	0.67	
Sikorsky	S-61A	1961	21500	9763	0.45	CAF designated CH-124 (SH-3 ASW)
Sikorsky	S-61L	1961	19000	11792	0.62	Also known as the Mark II
Sikorsky	CH-54A	1964	42000	18217	0.43	
Sikorsky	CH-3C	1964	22050	13255	0.60	Also known as S-61R
Sikorsky	CH-53A	1966	40000	21700	0.54	S-65A Also known as CH-53A/B Skycrane
Sikorsky	CH-54B	1966	42000	19234	0.46	S-64F
Lockheed	AH-56A	1968	22550	12215	0.54	
Sikorsky	CH-53D	1969	42000	23485	0.56	
Sikorsky	S-64E	1969	42000	19178	0.46	Also known as CH-54 Skycrane
Sikorsky	S-76	1979	10300	5600	0.54	Also known as Mark II
Sikorsky	UH-60A	1979	20250	10624	0.52	Also known as Night Hawk
Sikorsky	CH-53E	1980	73500	33226	0.45	S-61R (based on 1G w/Ext Payload)
Sikorsky	S-75	1985	10000	6421	0.64	Advanced Composite Airframe Program ACAP
Sud Aviation	SA-321	1966	26455	14420	0.55	Also known as Super Frelon (Hornet)
Westland	WG-13	1972	9500	5210	0.55	
Westland	Lynx	1977	10000	5683	0.57	
Westland	30 (?)	1982	12350	6982	0.57	

RELATIVE WEIGHT-EMPTY ESTIMATES (CONT'D)

DATA SHEET - RUSSIAN HELICOPTERS

MFGR	MODEL	YEAR	MAX FLYING WT	WT EMPTY	REL. WT	COMMENTS
USSR	MI-1	1951	4960	3925	0.79	
USSR	MI-2	1965	8175	5229	0.64	
USSR	MI-4	1953	17200	11715*	0.68	Estimated
USSR	MI-6	1959	93700	60055	0.64	
USSR	MI-8	1965	26450	15026	0.57	
USSR	MI-10	1960	83775	54410	0.65	
USSR	MI-14	1973	30865			Also known as the Haze
USSR	MI-17	1982	28660	15653	0.55	NATO designated Hip-H
USSR	MI-24	1973	24250	18520	0.76	Also designated (NATO) Hind
USSR	MI-26	1982	123400	62181	0.50	
USSR	KA-25	1961	16100	9700	0.60	Ship-Based Antisubmarine Warfare
USSR	KA-26	1970	7165	4300	0.60	
USSR	KA-25K	1967	16100	9700	0.60	Crane helicopter
USSR	V-12	1969	231500	142000	0.61	(Estimated)
Tishchenko*	SDS-52	1983	129210	69480	0.54	(Estimated)
Tishchenko	SA-15	1983	38760	18040	0.47	(Estimated)
Tishchenko	SA-24	1983	60100	26480	0.44	(Estimated)
Tishchenko	SA-52	1983	131375	65510	0.50	(Estimated)
Tishchenko	TA-15	1983	38500	19740	0.51	
Tishchenko	TA-52	1983	130600	74646	0.57	

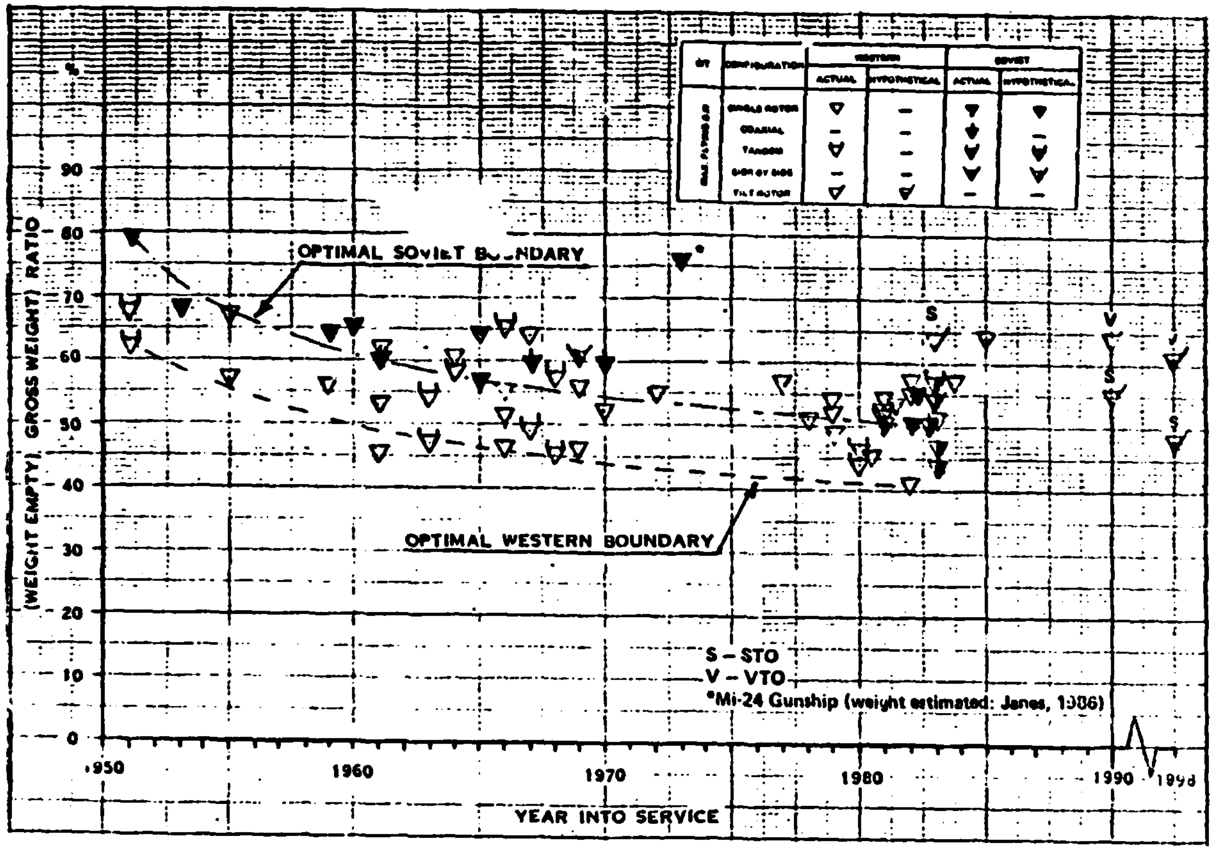


Figure 1.1 Temporal trends in the relative empty weights of Western rotorcraft and Soviet helicopters

decisively lower, as indicated by the optimal boundaries. Furthermore, looking at $\bar{W}_e$ values for Soviet hypothetical helicopters, especially of the single-rotor configuration, it appears that the Soviets hope to close the weight gap existing with the West, and are probably working in that direction.

3. With respect to the single-rotor and tandem Western helicopter configurations, it appears that, in general, the same progress with time regarding weight-empty applies. In the USSR, the greatest progress in lowering the weight-empty ratio was made for single-rotor configurations. This progress is also projected for the future, as indicated by the values for the hypothetical machine.

   As to the tilt-rotor configuration, it is clear that the $\bar{W}_e$ level for the XV-15 aircraft presently in use is much higher, even for STOL operations, than the average for present-day helicopters. Current weight estimates for the V-22 tilt-rotor show that its weight-empty to gross-weight ratio for VTO conditions should be on the level of the XV-15 with STO, and for its STO gross weight, the V-22 weight-empty ratio should approach that of some current helicopters. It can also be seen from Fig. 1.1 that the projected values of the $\bar{W}_e$ ratio of the hypothetical tilt-rotor (Ref. 3) are expected to be even better than for the V-22.

4. Moderate improvements in the weight-empty to gross-weight ratio from the 1960s to the present are partially due to further improvements in weight aspects of engines, but also probably reflect progress in structural weights of all other major helicopter components. In order to obtain a better picture of this aspect, the contribution of component weights and changes with time will be seperately examined.

1.2.3 Effect of Rotorcraft Size on Relative Weight-Empty Levels.

In order to examine whether or not there is any definite trend regarding the influence of rotorcraft size — as expressed through its maximum flying gross weight — on the weight-empty to maximum flying gross-weight ratios, $\bar{W}_e$ values in Table 1.1 were plotted vs. W_{max} on the semi-log scale (Figure 1.2). Looking at this figure, the following can be noted:

1. Since the so-called optimal boundary may be interpreted as an indication of the state-of-the-art potential, it can be clearly seen that as far as Western helicopt are concerned, equally low $\bar{W}_e$ ratios can, in principle, be achieved for small, as well as large helicopters. However, looking at the overall distribution of points representing the Western helicopters in Figure 1.2, it can be determined that, on the average, there is some improvement in the ive weight-empty with size as far as pure helicopters are concerned. Data for Soviet helicopters — as expressed through optimal boundaries and the overall distribution of points — seems to support the trend of relative weight improvement with size.

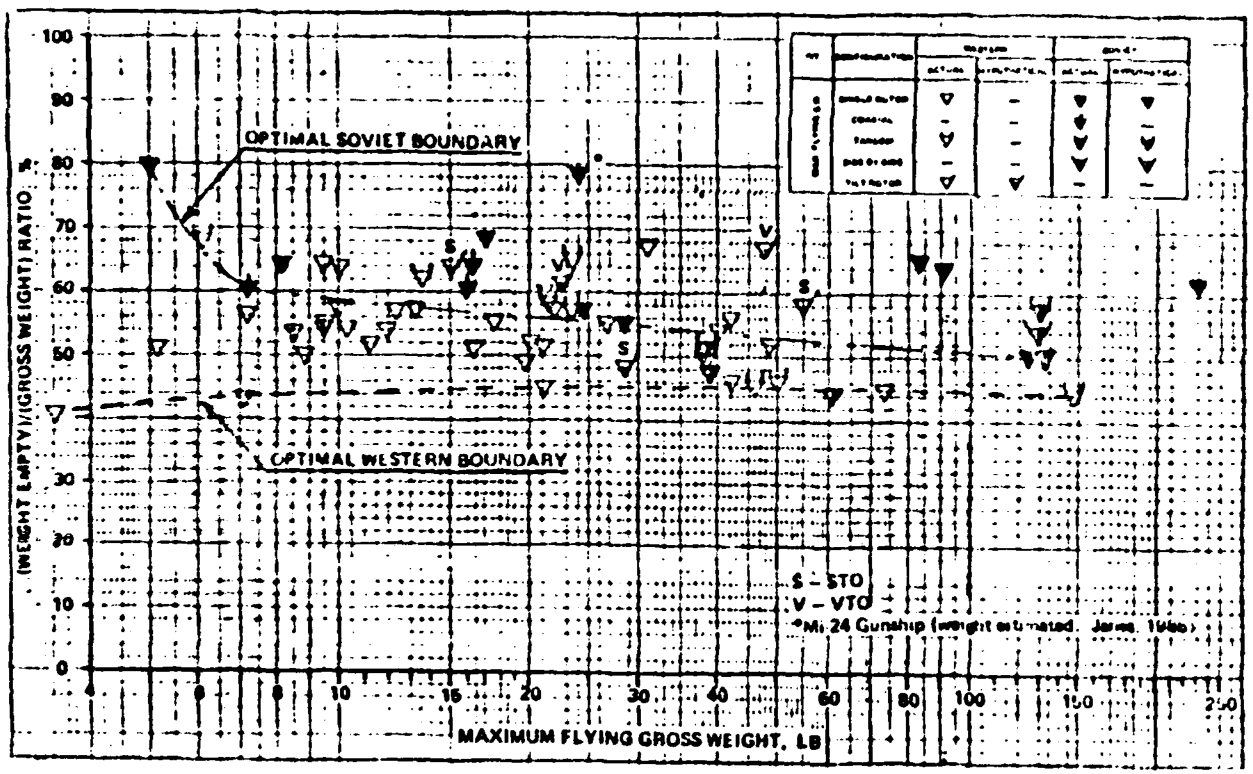


Figure 1.2 Gross weight related trends in relative empty weights

2. In order to get a better idea regarding the relationship between the relative weight-empty of a rotorcraft and its size, the effects of the rotorcraft maximum flying gross weight on the relative weights of all major structural components should be examined. This will be done in a way similar to the weight-empty case by plotting the relative weight of each of the major components vs. maximum flying gross weight.

1.3 Trends in Relative Weights of Main-Rotor Blades

1.3.1 General

As in the preceding case of relative weight empty, the relative weight of the main-rotor blades ($\overline{W}_{bl}$) is defined with respect to the maximum operational gross weight of the rotorcraft:

$$\overline{W}_{bl} = W_{bl}/W_{max}). \tag{1.2}$$

where W_{bl} is the actual weight of the blades. Although the weight of main--rotor blades is not the largest contributor to the empty weight of the aircraft, its influence on the $\overline{W}_e$ level goes beyond its direct fractional participation in that quantity. This is due to the magnitude of the centrifugal force generated by the blades which, in itself, is proportional to the blade weight and thus, strongly influences the weight of the hubs and hinges. Furthermore, the blades and hubs, together, form the lifting system; representing the most important assembly of a rotorcraft. For this reason, trends in the relative weight of the main-rotor blades are very important to the rotorcraft designer. Trends in main-rotor blade weights for a relatively large number of Western and Soviet helicopters, covering the time span from the early 1950s to the present, and even beyond, are assembled and presented in Table 1.2. Inputs for Western rotorcraft presented in this table were chiefly obtained from weight statements of various helicopter manufacturers, while this information for Soviet machines was obtained from Ref. 4. Both temporal and size-related trends in $\overline{W}_{bl}$ are shown in this table.

1.3.2 Temporal Variations of $\overline{W}_{bl}$ Ratios

Temporal variations in relative main-rotor blade weights are given in Figure 1.3. The following observations can be made from an examination of this figure.

1. With respect to Western helicopters, it appears that as far as the potential of achieving low $\overline{W}_{bl}$ values, as expressed by the optimal boundary, the Western industry, even in the early 1950s, could produce relative blade weights not much higher than those of contemporary helicopters. Looking at the overall distribution of points representing Western designs, one finds that, on the average, only a slight decline in $\overline{W}_{bl}$ values with time can be noticed. This temporal trend exists in spite of the appearance of new advanced materials with better and better strength-to-specific-weight ratios. One may expect, hence, that these new materials would contribute to the decrease in $\overline{W}_{bl}$ levels. However, such constraints as rotor axial moment of inertia and blade coning angle requirements do not permit one to take full advantage of the material potential in practical designs. This subject is more thoroughly investigated in the Appendix to Chapter 2. It is also interesting to note that the relative scatter of Western points is not very large. With respect to the tilt-rotor configuration, $\overline{W}_{bl}$ values of the XV-15 based on STO operation are even slightly better than the optimal boundaries for pure helicopters. The XV-15 points for VTO operations are slightly above the optimal boundary.

TABLE 1.2

RELATIVE BLADE WEIGHT ESTIMATES

DATA SHEET - WESTERN HELICOPTERS

MFGR	MODEL	YEAR	MAX FLYING WT	BLADE WTS	REL. WT	COMMENTS
Aerospatiale	SA-330J	1978	16315			
Aerospatiale	SA-365N	1981	8818			
Aerospatiale	AS-332L	1981	18410			
Aerospatiale	365	1983	[illegible]			
Agusta	A-109A	1976	5732			
Agusta/Sikorsky	AS-61N1	1984	22000			
Bell	UH-1A	1959	7200	343.0	0.0476	Teetering Rotor
Bell	UH-1B	1961	8500	382.0	0.0450	Teetering Rotor
Bell	UH-1D/H	1963	9500			Teetering Rotor
Bell	AH-1G	1967	9500			
Bell	UH-1N	1970	11200			
Bell	214A	1972	13000	770.0	0.0592	
Bell	OH-58C	1978	3200	190.0	0.0594	
Bell	412	1981	11900			
Bell	214ST	1982	17500			
Bell	XV-15	1983	15000	493.0	0.0329	
Bell/Boeing	V-22	1990e	55000			
Bell/Boeing	V-22	1990	47500			
Boeing Vertol	CH-47A	1963	38550			
Boeing Vertol	CH-47A	1963	33000	1426.0	0.0432	Steel D-Spar
Boeing Vertol	CH-46A	1964	21400	832.0	0.0389	Steel D-Spar
Boeing Vertol	CH-46E	1966	23300			
Boeing Vertol	CH-47B	1967	40000	1690.0	0.0423	
Boeing Vertol	CH-46F	1968	23300	986.0	0.0423	
Boeing Vertol	CH-47C	1968	46000	1690.0	0.0367	
Boeing Vertol	YCH-62A	1979	148000	6264.0	0.0423	Fibreglass
Boeing Vertol	YUH-61A	1979	19700	872.0	0.0443	
Boeing Vertol	CH-47D	1980	50000	2130.0	0.0426	
Boeing Vertol	234LR	1981	48500			
Eurofar	Hypo.	1990	[illegible]			
Eurofar	Hypo.	1990	22491			
McDonnell-Douglas	500E	1982	3550			
McDonnell-Douglas	AH-64A	1983	21000	637.0		
MBB	BO105C/D	1966	5114	268.2	0.0524	
MBB/Kawasaki	BK-117A-3	1981	7055	377.1	0.0535	
Piasecki	HUP-2	1951	6100	320.0	0.0524	
Piasecki	H-21C	1951	15000	632.0	0.0421	
Piasecki	YH-16A	1955	38000	2200.0	0.0579	Aluminum Skin & Honeycomb
Sikorsky	H-34A	1955	13300	640.0	0.0481	
Sikorsky	H-37A	1955	31000	1752.0	0.0565	
Sikorsky	S-61A	1961	21500			
Sikorsky	S-61L	1961	19000			
Sikorsky	CH-54A	1964	42000			
Sikorsky	CH-3C	1964	22050	857.0	0.0389	
Sikorsky	CH-54B	1966	42000	2180.0	0.0519	
Sikorsky	CH-53A	1966	40000	2195.0	0.0549	
Lockheed	AH-56A	1968	22550			
Sikorsky	CH-53D	1969	42000			
Sikorsky	S-64E	1969	42000			
Sikorsky	S-76	1979	10300	355.0	0.0755	
Sikorsky	UH-60A	1979	20250	841.1	0.0415	
Sikorsky	CH-53E	1980	73500	2884.9	0.0393	
Sikorsky	S-75	1985	10000	360.0	0.0360	ACAP
Sud Aviation	SA-321	1966	26455			
Westland	WG-13	1972	9500	0.408	0.0472	
Westland	Lynx	1977	[illegible]			
Westland	30 [illegible]	1982	[illegible]			

RELATIVE BLADE-WEIGHT ESTIMATES (CONT'D)

DATA SHEET - RUSSIAN HELICOPTERS

MFGR	MODEL	YEAR	MAX FLYING WT	BLADE WT	REL. WT	COMMENTS
USSR	MI-1	1951	4960	350.6	0.0707	Riveted Construction
USSR	MI-2	1965	8175	363.8	0.0445	Extruded Duralumin Spar
USSR	MI-4	1953	17200	1146.6	0.0666	Presumably Extruded Duralumin Spar
USSR	MI-6	1959	93700	7772.6	0.0830	Round Steel-Tube Spar
USSR	MI-6	1959	93700	7056.0	0.0753	
USSR	MI-6	1959	93700	5953.5	0.0635	
USSR	MI-8	1965	26450	1477.4	0.0559	Extruded Duralumin Spar
USSR	MI-8	1965	26450	1278.9		Glass Fibre
USSR	MI-10	1960	83775	7772.6	0.0928	Round Steel-Tube Spar
USSR	MI-14	1973	30865			
USSR	MI-17	1982	28660			
USSR	MI-24	1973	24250			
USSR	MI-26	1982	123400			
USSR	KA-25	1961	16100			
USSR	KA-26	1970	7165	344.0	0.0480	Glass-Textolite
USSR	KA-25A	1967	16100			
USSR	V-12	1969	231500			
Tishchenko	SBS-52	1983	129210	4850.0	0.0375	
Tishchenko	SR-15	1983	38760	1358.0	0.0350	
Tishchenko	SR-26	1983	60100			
Tishchenko	SR-52	1983	131375	7166.0	0.0545	
Tishchenko	TA-15	1983	38500	1693.4	0.0440	
Tishchenko	TA-52	1983	130000	7166.0	0.0551	

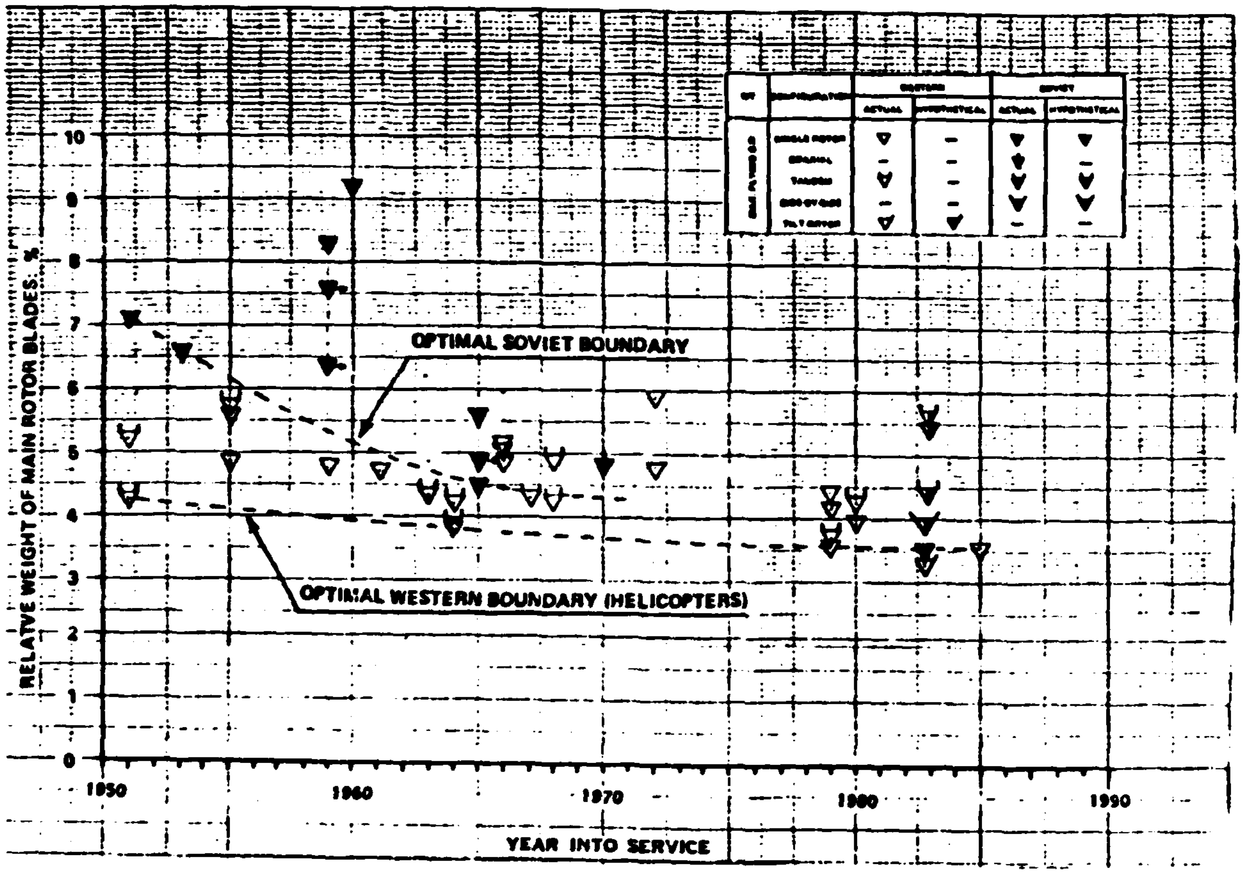


Figure 1.3 Temporal trend in relative weight of main-rotor blades

2. Unfortunately, the Soviet trends are not supported by statistical data as extensive and reliable as that in the West, but still, one may make a fair judgemental attempt as to the following observations: From the early days of the Mil Mi-1 and Mi-4, considerable progress relating to the relative blade weight was made. This was visible from the case of the Mi-6 (1969) points showing a reduction in $\bar{W}_{bl}$ from 8.3 percent for their original blades having steel tubular spars, to 6.35 percent for later designs (probably fiber glass). The same trend was observed for the Mi-8, where the relative blade weight was reduced from 5.59 percent for extruded Duralumin spars, to 4.84 percent for the glass fiber design. For the Mil Mi-2 design which was basically put into service in 1966, $\bar{W}_{bl}$ = 4.46 percent is not much different than the optimal Western values. As far as projections for the future are concerned, points for the hypothetical helicopters seem to indicate that the Soviets hope to attain the $\bar{W}_{bl}$ levels represented by the optimal Western boundaries.

1.3.3 Effect of Rotorcraft Size on $\bar{W}_{bl}$

The effect of rotorcraft size on the relative weight of main-rotor blades is examined by plotting $\bar{W}_{bl}$ vs. maximum flying gross weight (Figure 1.4). Looking at this figure, the following observations can be made.

1. The shape of the optimal boundary for Western helicopters, as well as the distribution of points seems to indicate that the $\bar{W}_{bl} = f(W_{max})$ function attains its optimum value for medium size helicopters of the 10,000 to 20,000-pound maximum gross-weight class. There seems to be a marked trend for an increase in $\bar{W}_{bl}$ values as the rotorcraft gross weight decreases from the 10,000-pound level. By contrast, only a slight trend toward an increase in the relative blade-weight level can be noted as the helicopter gross weight increases beyond the 25,000-pound level. Within the 10,000-pound to almost 150,000-pound maximum gross-weight range, the average $\bar{W}_{bl}$ level for Western helicopters does not seem to be much different than about 4 percent. It should also be noted that with few exceptions, the scatter of Western points from the 4 percent level is not very high.

2. With respect to Soviet helicopters, it is somewhat difficult to establish the optimal boundary at higher maximum flying gross-weight values other than that corresponding to the Mi-8 (approximately at the 26,000-pound point on the graph depicted in Figure 1.4), since this investigator has been unable to secure actual blade weights of such new designs as the Mil Mi-26 and Mi-17. It was shown in Refs. 1 and 5 that the Mi-26 is quite similar in many respects to the Tishchenko hypothetical helicopter; thus, it may be assumed that its blade weights would also be not much different from those of the Tishchenko SR-52 helicopter. Based on this assumption, optimal boundaries for Soviet

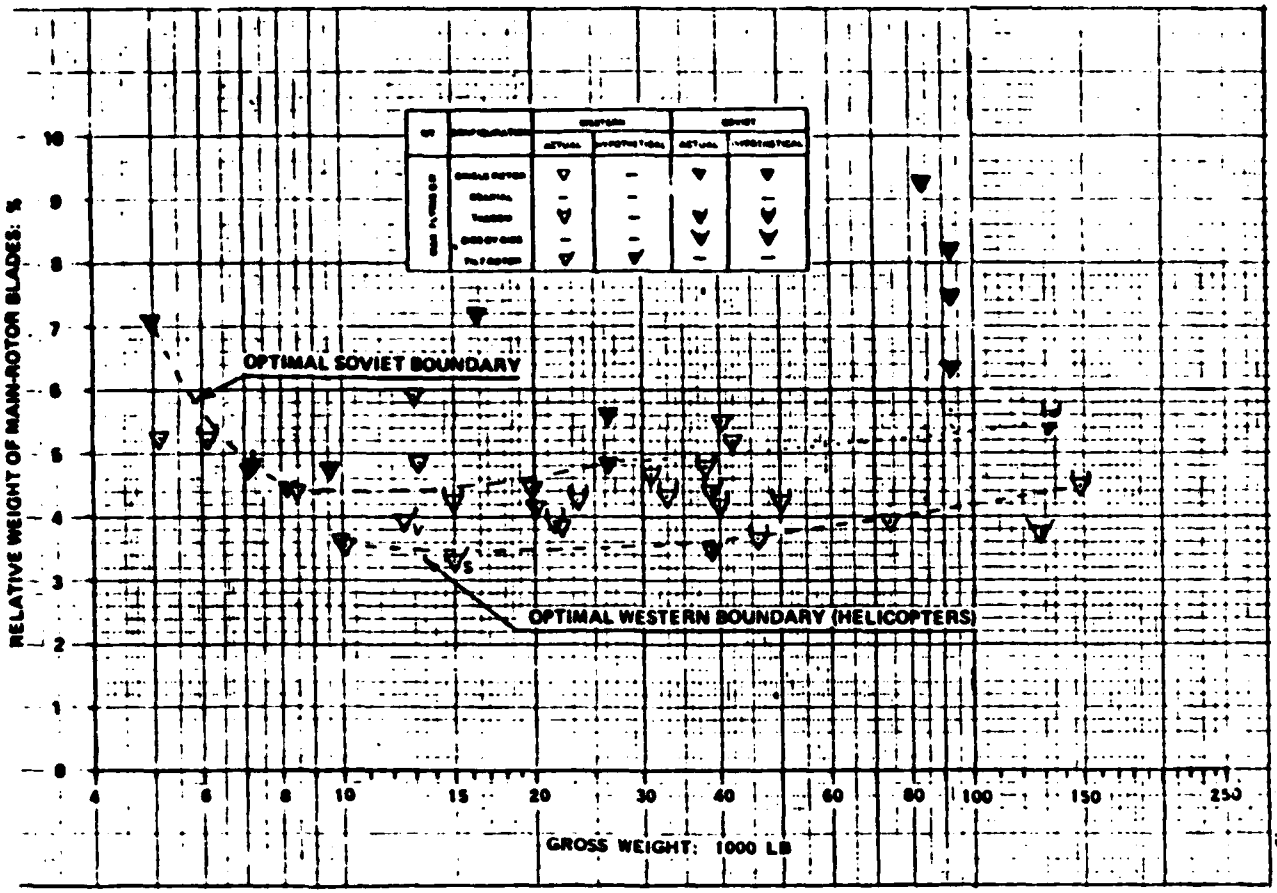


Figure 1.4 Relative weights of main-rotor blades vs. maximum gross weight

helicopters was extended beyond the Mi-8 point. Looking at the so-established optimal boundary, as well as the actual points, it appears that the same conclusions as those derived for Western helicopters appear feasible. The values of $\bar{W}_{bl}$ tend to attain their optimum level for the 10,000 to 20,000-pound maximum gross-weight class and, outside of this boundary, they tend to sharply increase with a decrease in $\bar{W}_{max}$ values, and increase only moderately as the $\bar{W}_{max}$ level becomes higher than 20,000 pounds. As far as the general trend is concerned, it appears that relative blade weights of Soviet helicopters tend to be slightly higher than those of their Western counterparts. As to future trends – as expressed through data for the hypothetical helicopters[4] – one would find that for the single-rotor helicopter in the upper medium gross-weight class (about 40,000 pounds), they expect to achieve $\bar{W}_{bl}$ levels as good as the optimal ones for Western machines. However, for large helicopters of the Mi-26 class, they seem to accept higher relative blade-weight values than those of the West for both single-rotor and tandem helicopters. By contrast, for the side-by-side configuration, they expect to do better than has been accomplished in the West. It should be noted that the trends represented by the Soviet hypothetical tandem and side-by-side helicopters are probably not very significant, as there is no indication that they are developing any large helicopters of these configurations.

1.4 Trends in Relative Weights of Main-Rotor Hubs and Hinges

1.4.1 General

Relative weight of the main-rotor hubs and hinges ($\overline{W}_h$) is related, as always in this study, to the maximum flying gross weight of the rotorcraft, and is defined as follows:

$$\overline{W}_h = W_h/W_{max} \tag{1.3}$$

where W_h is the weight per aircraft of the main rotor hubs and hinges. Similar to the preceding case of main-rotor blades, the necessary inputs required to establish trends for both temporal and size variations of the $\overline{W}_h$ levels were obtained from the weight statements of the manufacturers of Western rotorcraft, and from Reference 4 for Soviet helicopters. These inputs are presented in tabular form in Table 1.3.

1.4.2 Temporal Variation of $\overline{W}_h$ Ratios

Temporal variations in relative weights of main-rotor hubs and hinges are shown in Figure 1.5. Looking at this graph, the following trends can be detected.

1. It appears that for Western helicopters, the so-called optimal boundary sustained an almost constant level of slightly below a 4-percent value from the fifties to the early seventies. Then, in the eighties, it descended to a level of slightly below 3 percent. The decreasing trend in $\overline{W}_h$ values, similar to that of the optimal boundary, can also be noted by examining the overall distribution of Western helicopter points in Figure 1.5 and drawing an imaginary line representing the mean-value line through these points. It is interesting to note that for the tilt-rotor represented by the XV-15, $\overline{W}_h$ values based on both STO and VTO maximum gross weights are quite close to the optimal boundary for Western helicopters. One should also note a considerable drop in the $\overline{W}_h$ level in those cases where steel hubs were replaced by those made of titanium. In turn, replacing titanium hubs with hubs made of composite fibre materials led to a further reduction in $\overline{W}_h$. This clearly illustrates the influence of materials having better strength-to-specific-weight ratios.

2. It is difficult to detect, with a degree of certainty, the temporal trends in the $\overline{W}_h$ values of Soviet helicopters because of the relatively limited amount of data available to this investigator. However, even on the basis of the limited information presented in Figure 1.5, the following tentative observations can be made. Although, through the years, the $\overline{W}_h$ levels of Soviet helicopters generally were above those for Western machines, there is an exception in the Mi-2 case, where its $\overline{W}_h$ level is on the optimal boundary for Western helicopters. As far as future trends and efforts are concerned, there appears no projection (and probably, little effort) to attain the optimal Western $\overline{W}_h$ level for all configurations and sizes of helicopters. This latter aspect will be more clearly visible in Figure 1.6 and thus, it will be more thoroughly discussed in the following section of this report.

TABLE 1.3

RELATIVE HUB AND HINGE WEIGHT ESTIMATES

DATA SHEET - WESTERN HELICOPTERS

MFGR	MODEL	YEAR	MAX FLYING WT	HUB & HINGE WTS	REL. WT	COMMENTS
Aerospatiale	SA-330J	1970	16315			
Aerospatiale	SA-365N	1981	8818			
Aerospatiale	AS-332L	1981	18410			
Aerospatiale	365	1983	8928			
Agusta	A-109A	1976	5732			
Agusta/Sikorsky	AS-61R	1964	22000			
Bell	UH-1A	1959	7200	262.0	0.0364	
Bell	UH-1B	1961	8500	363.0	0.0427	
Bell	UH-1B/M	1963	9500			
Bell	AH-1G	1967	9500			
Bell	UH-1N	1970	11200			
Bell	214-A	1972	13000	730.0	0.0562	
Bell	OH-58C	1978	3200	91.0	0.0284	
Bell	412	1981	11900			
Bell	214ST	1982	17500			
Bell	XV-15	1983	15000	370.0	0.0247	
Bell/Boeing	V-22	1990+	55000			
Bell/Boeing	V-22	1990	47500			
Boeing Vertol	CH-47A	1963	38550	1428.0	0.0371	
Boeing Vertol	CH-47A	1963	33000	1428.0	0.0433	
Boeing Vertol	CH-46A	1964	21400	932.0	0.0436	
Boeing Vertol	CH-46E	1966	23300			
Boeing Vertol	CH-47B	1967	40000	1627.0	0.0407	
Boeing Vertol	CH-46F	1968	23300	912.0	0.0391	
Boeing Vertol	CH-47C	1968	46000	1685.0	0.0366	
Boeing Vertol	YCH-62A	1979	148000	7306.0	0.0494	
Boeing Vertol	YUH-61A	1979	19700	519.0	0.0263	
Boeing Vertol	CH-47D	1980	50000	1524.0	0.0305	
Boeing Vertol	234LR	1981	48500			
Eurofar	Hypo.	1990	20665			
Eurofar	Hypo.	1990	22491			
McDonnell-Douglas	500E	1982	3550			
McDonnell-Douglas	AH-64A	1983	21000			
MBB	BO105C/B	1966	5114	192.0	0.0375	Hingeless, Titanium
MBB/Kawasaki	BK-117A-3	1981	7055	198.5	0.0281	Hingeless, Titanium
Piasecki	HUP-2	1951	6100	270.0	0.0443	
Piasecki	H-21C	1951	15000	634.0	0.0423	
Piasecki	HUP-4	1953	5740	226.0	0.0394	
Sikorsky	H-34A	1955	13300	592.0	0.0445	
Sikorsky	H-37A	1955	31000	1748.0	0.0564	
Sikorsky	S-61A	1961	21500			
Sikorsky	S-61L	1961	19000			
Sikorsky	CH-54A	1964	42000			
Sikorsky	CH-3C	1964	22050	857.0	0.0389	
Sikorsky	CH-53A	1966	40000	2668.0	0.0667	
Sikorsky	CH-53A	1966	40000	1978.0	0.0495	Titanium Blades
Sikorsky	CH-54B	1966	42000	1760.0	0.0419	Titanium Blades
Lockheed	AH-56A	1968	22550	1143.0	0.0507	Titanium Blades
Sikorsky	CH-53D	1969	42000			
Sikorsky	S-64E	1969	42000			
Sikorsky	S-76	1979	10300	375.0	0.0364	
Sikorsky	UH-60A	1979	20250	606.0	0.0299	
Sikorsky	CH-53E	1980	73500	3472.0	0.0472	Titanium Blades
Sikorsky	CH-53E	1980	73500	2619.0	0.0356	Fiberglass
Sikorsky	S-75	1985	10000	310.0	0.0310	ACAP
Sud Aviation	SA-321	1966	26455			
Westland	WG-13	1972	9500	384.0	0.0404	Titanium
Westland	Lynx	1977	10000			
Westland	30 (?)	1982	12350			

RELATIVE HUB AND HINGE WEIGHT ESTIMATES (CONT'D)

DATA SHEET - RUSSIAN HELICOPTERS

MFGR	MODEL	YEAR	MAX FLYING WT	HUB & HINGE WT	REL WT	COMMENTS
USSR	MI-1	1951	4960	271.2	0.0547	
USSR	MI-2	1965	8175	291.1	0.0356	
USSR	MI-4	1953	17200	937.1	0.0545	
USSR	MI-6	1959	93700	7331.6	0.0782	
USSR	MI-8	1965	26450	1334.0	0.0504	
USSR	MI-10	1960	83775	7331.6	0.0876	
USSR	MI-14	1973	30865			
USSR	MI-17	1982	28660			
USSR	MI-24	1973	24250			
USSR	MI-26	1982	123400			
USSR	KA-25	1961	16100			
USSR	KA-26	1970	7165			
USSR	KA-25K	1967	16100			
USSR	V-12	1969	231500			
Tishchenko*	SBS-52	1983	129210	4740.8	0.0367	
Tishchenko	SA-15	1983	38760	1186.3	0.0306	
Tishchenko	SA-24	1983	60100			
Tishchenko	SR-52	1983	131375	6835.5	0.0520	
Tishchenko	TA-15	1983	38500	1865.4	0.0485	
Tishchenko	TA-52	1983	130000	6174.0	0.0475	

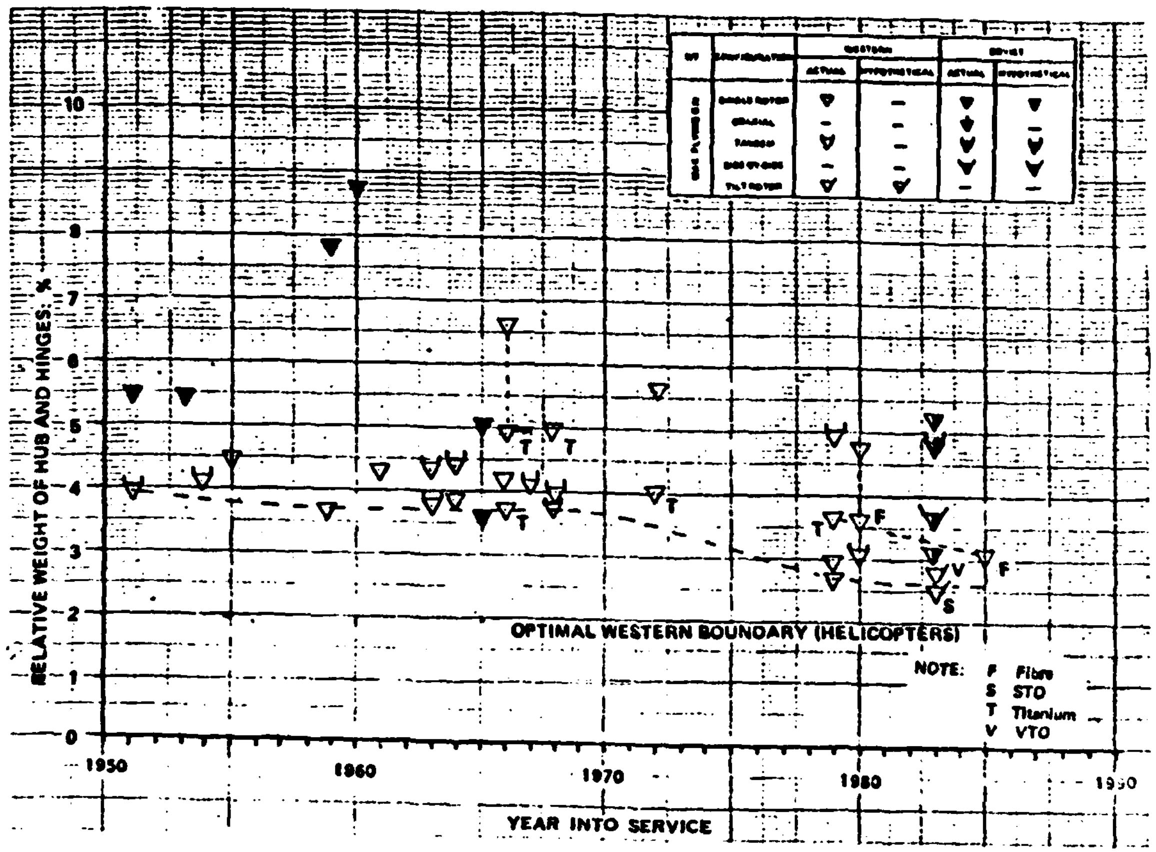


Figure 1.5 Trends in temporal variation in the relative weights of hubs and hinges of Western rotorcraft and Soviet helicopters

1.4.3 Influence of Rotorcraft Size ($\bar{W}_{max}$) on $\bar{W}_h$ Levels

Looking at Figure 1.6 where relative hub weights vs. $\bar{W}_{max}$ are shown the following trends seem to emerge.

1. When one looks at the optimal boundary for Western helicopters, it appears that the lowest $\bar{W}_h$ level of about 2.7% is achieved for the 20,000-pound maximum gross-weight class machines. For both lighter and heavier helicopters, the optimal $\bar{W}_h$ values tend to increase, reaching $\bar{W}_h \approx 3.9\%$ for the 5000 pound gross-weight, and about 6% for the 140,000-pound gross-weight machines. However, the overall distribution of the $\bar{W}_h$ points seem to suggest that, on the average, the relative weights of the hub and hinges stay at about the 4% level, although the scatter of $\bar{W}_h$ values is quite considerable. It is also clear that, as indicated in the preceding section, a transition to structural materials with better strength/specific weight ratios (e.g., from steel to titanium, or from titanium to composites) results in considerable weight savings. It is also interesting to note that for the tilt-rotor configuration (XV-15), the $\bar{W}_h$ value for the VTO is right on the helicopter optimal boundary, and for STO operations, even below that line.

2. There are not enough points for Soviet helicopters in Figure 1.6 to positively define an optimal boundary for $\bar{W}_h$ values. However, it appears that, in general, the relative hub and hinge weights of Soviet production helicopters are higher than those of their Western counterparts. The Mi-2 represents an exception, as its $\bar{W}_h$ point is right on the optimal boundary for Western helicopters. By contrast, points for the Mi-6 and Mi-10 are way above the Western trend with $\bar{W}_h \approx 7.8\%$ for the Mi-6 and about 8.8% for the Mi-10 helicopter. As to the indications regarding future trends, it should be noted that for the single-rotor configuration of the 38,000-pound gross-weight class, low $\bar{W}_h$ values of about 4% are visualized (right on the optimal boundary of Western helicopters), while for the large single-rotor machines of the Mi-26 gross-weight class ($\bar{W}_{max} \approx$ 130,000 lb), Soviet goals are more conservative ($\bar{W}_h \approx 6\%$). Projections for the side-by-side helicopters of the Mi-26 gross-weight class appear quite optimistic with $\bar{W}_h \approx 3.7\%$ – below the Western optimal boundary.

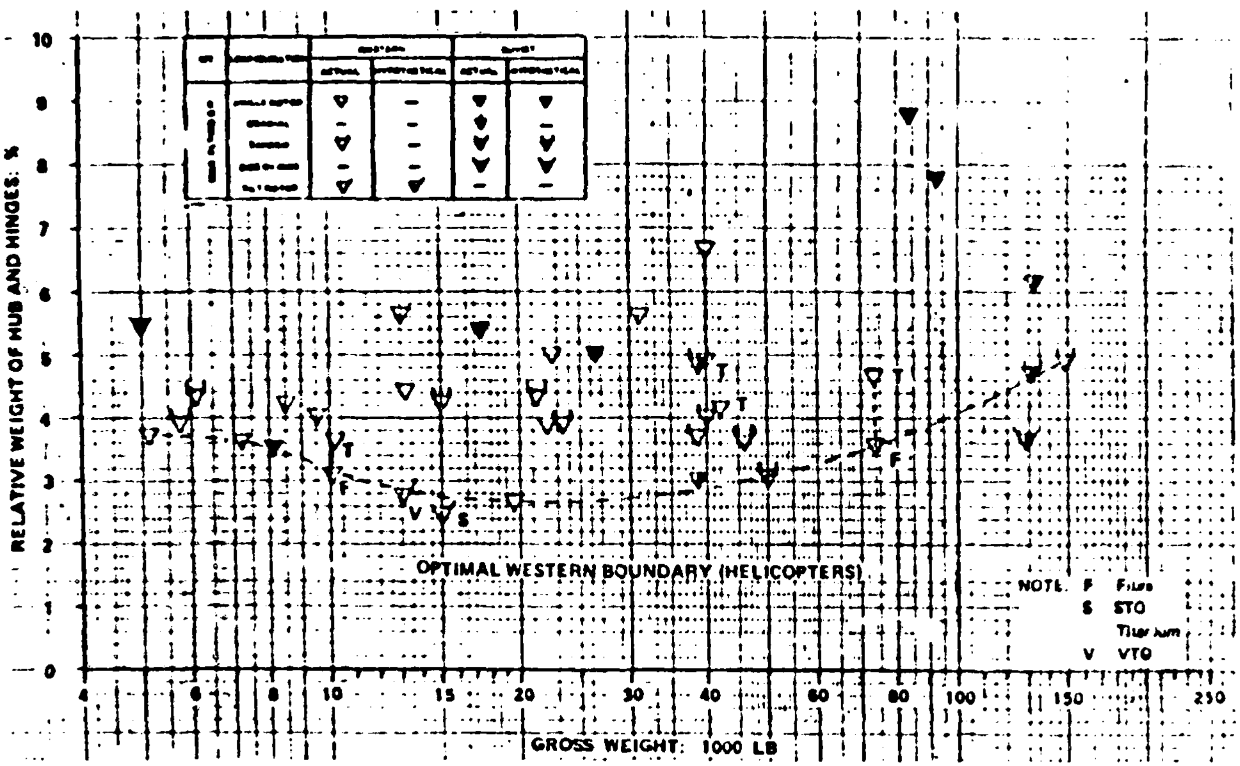


Figure 1 6 Relative weight trends of hubs and hinges vs. maximum aircraft gross weights for Western rotorcraft and Soviet helicopters

1.5 Trends in Relative Weights of Fuselages

1.5.1 General

The fuselage weight group of a rotorcraft is considered here – as in Ref. 1 – to consist of the following elements: (a) fuselage, (b) horizontal and vertical empennages, (c) engine nacelles, and (d) air induction system. The relative weight of the fuselage ($\overline{W}_f$) is defined as:

$$\overline{W}_f = W_f/W_{max} \qquad (1.4)$$

where W_f is the weight of the fuselage group, representing the sum of the weights of all the subcomponents listed above as items (a) through (d). Inputs, necessary to establish both temporal and size-related trends for relative fuselage weights, are presented in Table 1.4.

1.5.2 *Temporal Variations of $\overline{W}_f$ Ratios*

Temporal variations in relative weights of rotorcraft fuselages are presented in Figure 1.7, from which the following trends can be deduced.

1. With respect to Western rotorcraft, one should note that in spite of a considerable scatter of points, a general trend emerges which indicates a decrease in $\overline{W}_f$ with time. This trend becomes even more noticeable when the so-called optimal boundary is examined for $\overline{W}_f$ values. Also, looking at this boundary, one should note that relative fuselage weights for the crane configurations for both the Sikorsky CH-54 and the Boeing Vertol heavy-lift helicopter are below the line representing optimal $\overline{W}_f$ values of other Western configurations. Points corresponding to the tilt-rotor configuration as represented by the XV-15 show that the $\overline{W}_f$ value for VTO operations seems to be definitely above those representing other contemporary rotorcraft, while for the STO case, the $\overline{W}_f$ is within the higher helicopter values.

2. It is more difficult to establish temporal trends in $\overline{W}_f$ values for Soviet helicopters, since this investigator has no reliable data regarding fuselage weights for Russian rotorcraft of the seventies and eighties. However, as in the preceding cases, assuming that the hypothetical single-rotor helicopters closely resemble actually achievable weight levels, a tentative optimal boundary has been extended in Figure 1.7 between the 1968 and 1983 abscissas. Looking at this line and the general distribution of Soviet $\overline{W}_f$ points, one may conclude that, as in the West, there should be a trend in the USSR toward a decrease in $\overline{W}_f$ levels with time. Nevertheless, it appears that, as in the past, Soviet relative fuselage-group weights would remain somewhat above that of their Western counterparts.

1.5.3 Influence of Rotorcraft Size (W_{max}) on $\overline{W}_f$ Levels

The influence of the size of the rotorcraft, as expressed through its maximum flying gross weight, on the $\overline{W}_f$ level can be detected by examining Figure 1.8, where one may note the following:

TABLE 1.4

RELATIVE FUSELAGE WEIGHT ESTIMATES

DATA SHEET - WESTERN HELICOPTERS

MFGR	MODEL	YEAR	MAX FLYING WT	BODY WEIGHT	REL. WT	COMMENTS
Aerospatiale	SA-330J	1978	16315			
Aerospatiale	SA-365N	1981	8610			
Aerospatiale	AS-332L	1981	18410			
Aerospatiale	365	1983	8928			
Agusta	A-109A	1976	5732			
Agusta/Sikorsky	AS-61N1	1984	22000			
Bell	UH-1A	1959	7200	781.0	0.108	
Bell	UH-1B	1961	8500			
Bell	UH-1D/H	1963	9500			
Bell	AH-1G	1967	9500			
Bell	UH-1N	1970	11200			
Bell	214-A	1972	13000	1567.0	0.121	
Bell	OH-58C	1978	3200	373.0	0.117	
Bell	412	1981	11900			
Bell	214ST	1982	17500			
Bell	XV-15	1983	15000	1424.0	0.095	STO
Bell	XV-15	1983	13000	1424.0	0.110	VTO
Bell/Boeing	V-22	1990e	55000			
Bell/Boeing	V-22	1990	47500			
Boeing Vertol	CH-47A	1963	38550	4498.0	0.117	
Boeing Vertol	CH-47A	1963	33000	4279.0	0.133	
Boeing Vertol	CH-46A	1964	21400	2557.0	0.120	
Boeing Vertol	CH-46E	1966	23300			
Boeing Vertol	CH-47B	1967	40000	4305.0	0.108	
Boeing Vertol	CH-46F	1968	23300	2963.0	0.127	
Boeing Vertol	CH-47C	1968	46000	4343.0	0.094	
Boeing Vertol	XCH-62A	1979	148000	9328.0	0.063	
Boeing Vertol	YUH-61A	1979	19700	1463.0	0.074	
Boeing Vertol	CH-47D	1980	50000	4606.0	0.092	
Boeing Vertol	234LR	1981	48500			
Eurofar	Hypo.	1998	28665			
Eurofar	Hypo.	1998	22491			
McDonnell-Douglas	500E	1982	3250			
McDonnell-Douglas	AH-64A	1983	21000	1442.0	0.069	
MBB	BO105C.D	1966	5114	524.1	0.103	
MBB/Kawasaki	BK-117A-3	1981	7055	701.2	0.099	
Piasecki	HUP-2	1951	6100			
Piasecki	H-21C	1951	15000	2180.0	0.145	
Piasecki	HUP-4	1953	5740			
Sikorsky	H-34A	1955	13300			
Sikorsky	H-37A	1955	31000			
Sikorsky	S-61A	1961	21500	2050.7	0.095	
Sikorsky	S-61L	1961	19000.			
Sikorsky	CH-54A	1964	42000	2646.0	0.063	
Sikorsky	CH-3C	1964	22050			
Sikorsky	CH-53A	1966	40000	4712.7	0.118	
Sikorsky	CH-54B	1966	42000			
Lockheed	AH-56A	1968	22550	2015.0	0.089	
Sikorsky	CH-53D	1969	42000			
Sikorsky	S-64E	1969	42000			
Sikorsky	S-76	1979	10300	1112.0	0.108	
Sikorsky	UH-60A	1979	20250	1769.0	0.088	
Sikorsky	CH-53E	1980	73500	7651.0	0.104	
Sikorsky	S-75	1985	10000	979.0	[illegible]	
Sud Aviation	SA-321	1966	[illegible]			
Westla	WG-13	1972	9500			
Westland	Lynx	1977	10000			
Westland	[illegible]	1982	12350			

RELATIVE FUSELAGE WEIGHT ESTIMATES (CONT'D)

RUSSIAN HELICOPTERS

MFGR	MODEL	YEAR	MAX FLYING WT	BODY WT	REL. WT	COMMENTS
USSR	MI-1	1951	4960	751.9	0.152	
USSR	MI-2	1965	8175	981.2	0.120	
USSR	MI-4	1953	17200	2063.9	0.120	
USSR	MI-6	1959	93700	13384.4	0.143	
USSR	MI-8	1965	26450	3230.3	0.122	
USSR	MI-10	1960	83775	11245.5	0.134	
USSR	MI-14	1973	30865			
USSR	MI-17	1982	28660			
USSR	MI-24	1973	24250			
USSR	MI-26	1982	123480			
USSR	KA-25	1961	16100			
USSR	KA-26	1970	7165			
USSR	KA-25K	1967	16100			
USSR	V-12	1969	231500	28113.7	0.121	
Tishchenko*	SDS-52	1983	129210	9150.8	0.071	
Tishchenko	SR-15	1983	38760	4224.2	0.109	
Tishchenko	SR-24	1983	68100			
Tishchenko	SR-52	1983	131375	11466.0	0.087	
Tishchenko	TA-15	1983	38500	4809.1	0.125	
Tishchenko	TA-52	1983	130000	16537.5	0.127	

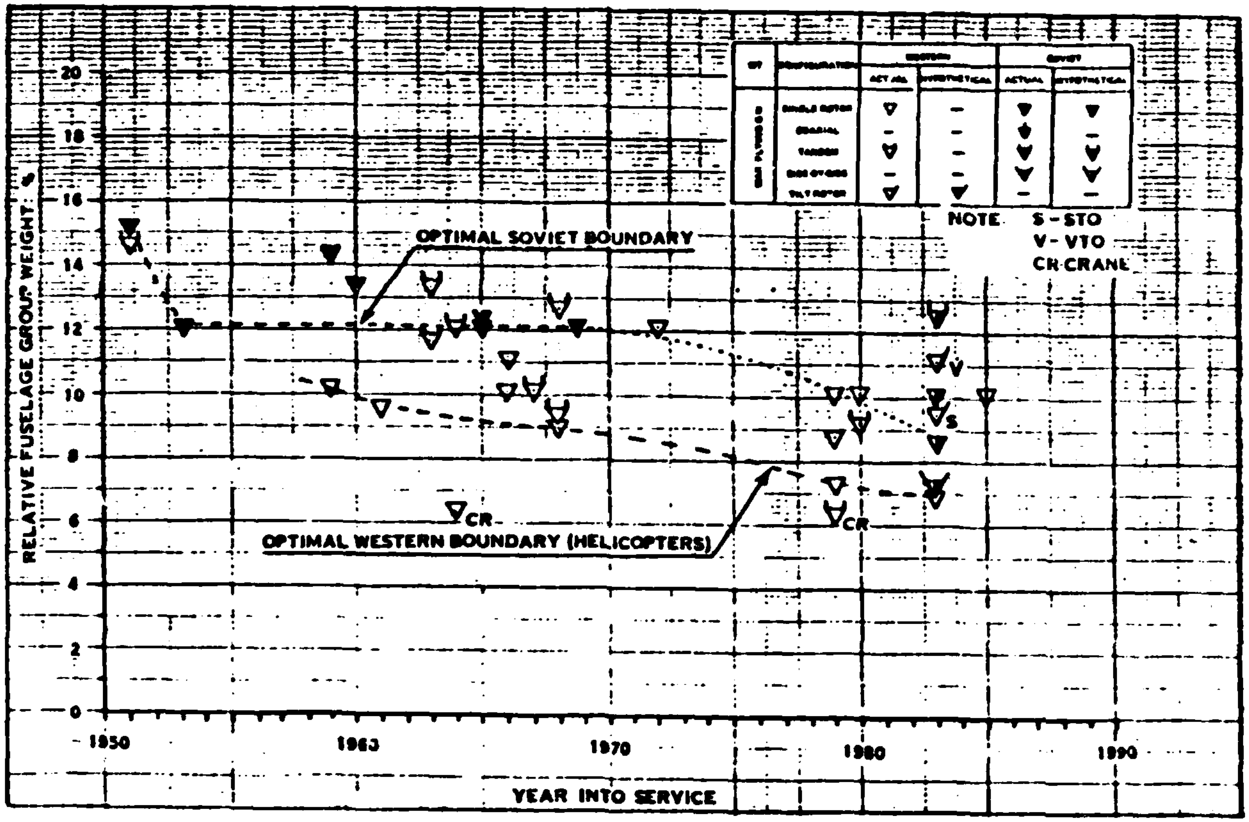


Figure 1.7 Temporal trends in relative weights of fuselage groups

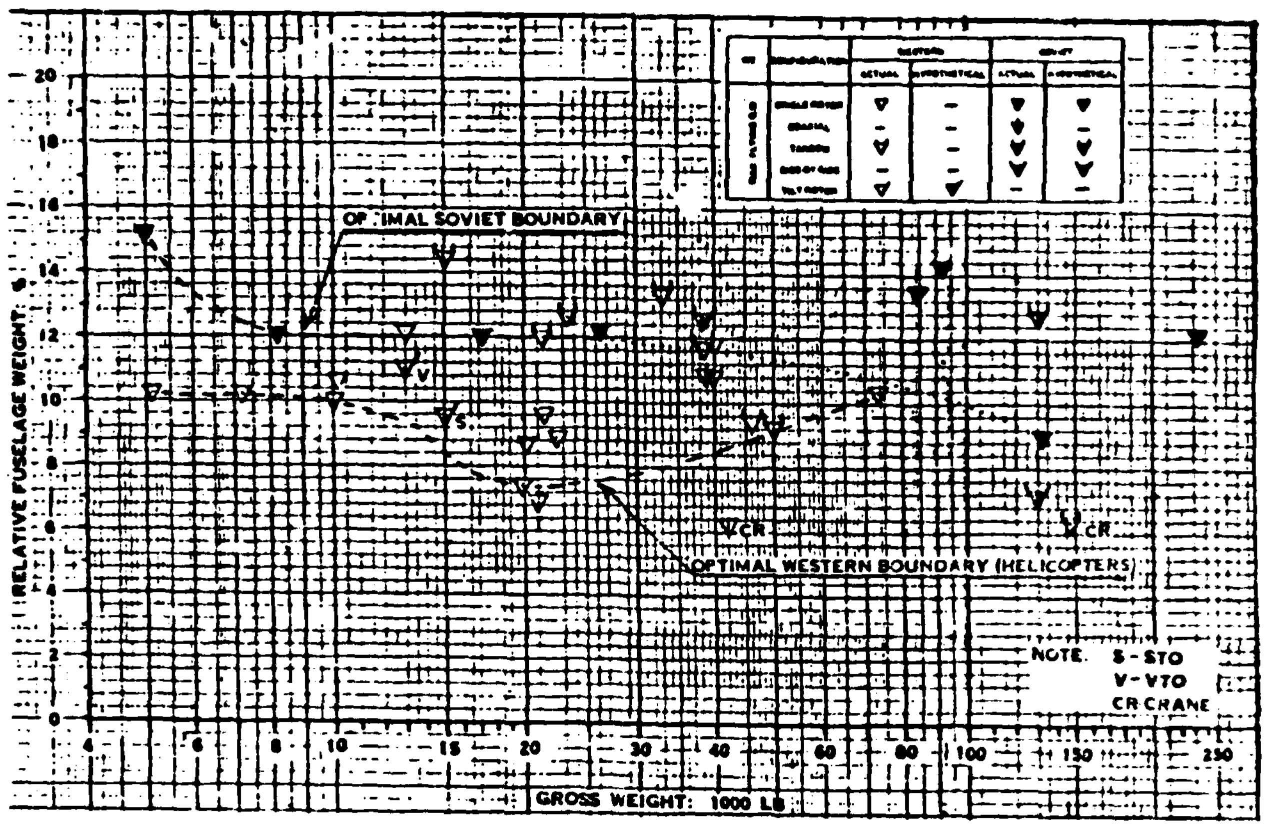


Figure 1.8 Trends in relative fuselage weights vs. maximum flying gross weights of rotorcraft

1. For Western helicopters, there is considerable scatter in the $\bar{W}_f$ values for each maximum gross-weight class. However, within this scatter, it appears that in general, the relative fuselage weights of the tandem configurations tend to be somewhat higher than those of the single-rotor type. Looking at the Western optimal boundary, one may presume that, potentially, the lowest $\bar{W}_f$ values could be achieved for the single-rotor, medium-size helicopters of the 20,000 to 25,000-pound maximum gross-weight class. As for the crane-type configurations, it is clear from Figure 1.8, as well as from Figure 1.7, that this helicopter category exhibits $\bar{W}_f$ levels considerably below those of their non-crane counterparts. For the tilt-rotor aircraft, deviations of the relative fuselage weight values, once judged within the context of their gross-weight class, seem more favorable when compared with helicopters than would appear from Figure 1.7.

2. In attempting to establish the gross-weight related trend in $\bar{W}_f$ values for Soviet helicopters, one would note from Figure 1.8 that once the point on the extreme left corresponding to an early design (Mi-1) is excluded, the relative fuselage weights of the Mi-2 through Mi-12 are consistently close to $\bar{W}_f \approx 12$ percent. The Mi-6 and Mi-10 form an exception, having $\bar{W}_f$ values of 14.3 and 13.4 percent, respectively. From a plot of points for Soviet helicopters for which data is available, it appears that, in general, their $\bar{W}_f$ values seem to be higher than for their Western counterparts represented by single-rotor configurations. With no substantial data available for relative fuselage weights of Soviet helicopters from the seventies and eighties, it is assumed that the $\bar{W}_f$ values derived from the single-rotor hypothetical helicopters of Ref. 4 should give an indication regarding the trend. Following this reasoning, it appears that Soviet designers are attempting to, and perhaps, already have achieved the same levels regarding relative fuselage weights as those in the West.

1.6 Trends in Relative Weights of Landing Gears

1.6.1 General

There are three basic types of landing gears being used in rotary-wing aircraft: (a) skids, (b) fixed, and (c) retractable. Within the most numerous group of (b), one may distinguish a special sub-group of taller-than-usual landing gears for cranes and heavy-lift helicopters. One may expect that the relative weight trends may be somewhat different for each of the above-mentioned types of landing gears. In addition, some investigators of the weight aspects of landing gears (i.e., Tishchenko et al[4]) tend to establish landing-gear trends separately for single-rotor and tandem configurations. However, this investigator believes that differences in the relative-weight trends of undercarriages for tandem and single-rotor helicopters are not large enough to warrant establishment of separate sub-groups in the present study.

The relative weight of a landing-gear group is defined as

$$\bar{W}_{lg} = W_{lg}/W_{max}. \tag{1.5}$$

where W_{lg} is the weight of the landing gear, and W_{max}, as always, represents the maximum flying weight of a rotorcraft. Inputs necessary to establish both temporal and size-related trends in $\bar{W}_{lg}$ values are presented in Table 1.5.

1.6.2 Temporal Trends in $\bar{W}_{lg}$ Ratios

Temporal variations in relative landing-gear weights are presented in Fig. 1.9, from which the following trends can be deduced.

1. With respect to Western rotorcraft, one would note that in the skid-type landing gears, there seems to be practically no change in relative weights over the years, with the $\bar{W}_{lg}$ value being slightly above 1% of W_{max}.One exception is the the MBB 105 helicopter with $\bar{W}_{lg} \approx 2\%$. Relative weights of the wheel-type fixed landing gears, when judged in the light of the so-called optimal boundary as well as actual distribution of points, seems to indicate some decline in $\bar{W}_{lg}$ values with time – approaching, in the eighties, the $\bar{W}_{lg} \approx 2.2\%$ level. As expected, the relative landing weight of the heavy-lift helicopter is considerably higher ($\bar{W}_{lg} = 4.3\%$) than those of the optimal boundary. One may expect that, in principle, $\bar{W}_{lg}$ values for retractable landing gears should be higher than those for their fixed- type counterparts. This trend can be noted from Fig. 1.9. However, the $\bar{W}_{lg} = 1.66\%$ value for the CH-53E helicopter represents an interesting exception. With respect to the tilt-rotor configuration, as exemplified by the XV-15, its $\bar{W}_{lg}$ is considerably higher for VTO operations, and slightly higher for STO operations than for helicopters.

2. Having no data available to this investigator on $\bar{W}_{lg}$ values for contemporary Soviet helicopters, the so-called optimal for relative landing-gear weights was established using inputs for hypothetical helicopters of Ref. 4. Except for the V-12 case, $\bar{W}_{lg}$ points for all other actual helicopters appear quite close to the optimal boundary. Looking at the trend suggested by this boundary, it appears that similar to the Western case, a

TABLE 15

RELATIVE LANDING-GEAR WEIGHT ESTIMATES

DATA SHEET - WESTERN HELICOPTERS

MFGR	MODEL	YEAR	MAX FLYING WT	LANDING-GEAR WT	REL. WT	COMMENTS
Aerospatiale	SA-330J	1970	16315			
Aerospatiale	SA-365N	1981	8818			
Aerospatiale	AS-332L	1981	18410			
Aerospatiale	365	1982	8928			
Agusta	A-109A	1976	5732			
Agusta/Sikorsky	AS-61R	1984	[illegible]			
Bell	UH-1A	1959	7200	80.0	0.0111	Skid
Bell	UH-1B	1961	8500			
Bell	UH-1D/H	1963	9500			
Bell	AH-1G	1967	9500			
Bell	UH-1N	1970	11200			
Bell	214-A	1972	13000	151.0	0.0116	Skid
Bell	OH-58C	1978	3200	34.4	0.0108	Skid (?)
Bell	412	1981	11900			
Bell	214ST	1982	17500			
Bell	XV-15	1983	15000	520.0	0.0349	STO
Bell	XV-15	1983	13000	520.0	0.0403	VTO
Bell/Boeing	V-22	1990s	55000			
Bell/Boeing	V-22	1990	47500			
Boeing Vertol	CH-47A	1963	38550	1060.0	0.0275	Fixed
Boeing Vertol	CH-47A	1963	33000	1060.0	0.0321	Fixed
Boeing Vertol	CH-46A	1964	21400			
Boeing Vertol	CH-46E	1966	23300			
Boeing Vertol	CH-47B	1967	40000	1059.6	0.0265	Fixed
Boeing Vertol	CH-46F	1968	23300	591.6	0.0254	Fixed
Boeing Vertol	CH-47C	1968	46000	1078.6	0.0234	
Boeing Vertol	XCH-62A	1979	148000	6403.6	0.0433	
Boeing Vertol	YUH-61A	1979	19700	465.0	0.0236	
Boeing Vertol	CH-47D	1980	50000	1124.0	0.0225	
Boeing Vertol	234LR	1981	48500			
Eurofar	Hypo.	1990	28665			
Eurofar	Hypo.	1990	22091			
McDonnell-Douglas	500E	1982	3550			
McDonnell-Douglas	AH-64A	1983	21000	518.0	0.0247	Fixed
MBB	BO105C/D	1966	5114	104.2	0.0204	Skid
MBB/Kawasaki	BK-117A-3	1981	7055	103.0	0.0147	Skid
Piasecki	HUP-2	1951	6100			
Piasecki	H-21C	1951	15000	501.0	0.0334	Fixed
Piasecki	HUP-4	1953	5700			
Sikorsky	H-34A	1955	13300			
Sikorsky	H-37A	1955	31000			
Sikorsky	S-61A	1961	21500			
Sikorsky	S-61L	1961	19000			
Sikorsky	CH-54A	1964	42000			
Sikorsky	CH-3C	1964	22050			
Sikorsky	CH-53A	1966	40000			
Sikorsky	CH-54B	1966	42000			
Lockheed	AH-56A	1968	22550	653.0	0.0290	
Sikorsky	CH-53D	1969	42000			
Sikorsky	S-64E	1969	42000			
Sikorsky	S-76	1979	10300	271.0	0.0263	Retractable
Sikorsky	UH-60A	1979	20250	458.0	0.0226	Fixed
Sikorsky	CH-53E	1980	73500	1219.0	0.0166	Retractable
Sikorsky	S-75	1985	10000	340.0	0.0340	ACAP, Retractable
Sud Aviation	SA-321	1966	26456			
Westland	WG-13	1972	9500			
Westland	Lynx	1977	10000			
Westland	[illegible]	1982	12350			

RELATIVE LANDING-GEAR WEIGHT ESTIMATES (CONT'D)

RUSSIAN HELICOPTERS

MFGR	MODEL	YEAR	MAX FLYING WT	LANDING-GEAR WT	REL. WT	COMMENTS
USSR	MI-1	1951	4960			
USSR	MI-2	1965	6175	228.4	0.0279	
USSR	MI-4	1953	17200	464.4	0.0270	
USSR	MI-6	1959	93700	2802.6	0.0300	
USSR	MI-8	1965	26450	685.3	0.0259	
USSR	MI-10	1960	63775	2361.1	0.0255	
	MI-10	1960	83775	5680.0	0.0678	
USSR	MI-14	1973	30865			
USSR	MI-17	1982	28660			
USSR	MI-24	1973	24250			
USSR	MI-26	1982	123400			
USSR	KA-25	1961	16100			
USSR	KA-26	1970	7165			
USSR	KA-25K	1967	16100			
USSR	V-12	1969	231500	9823.0	0.0425	
Tishchenko	SBS-52	1983	129210	3417.0	0.0265	
Tishchenko	SR-15	1983	38760	992.0	0.0256	
Tishchenko	SR-24	1983	60100			
Tishchenko	SR-52	1983	131375	2425.5	0.0185	
Tishchenko	TA-15	1983	38500	992.0	0.0256	
Tishchenko	TA-52	1983	130660	2910.9	0.0240	
Tishchenko	COR-52	1988	120000	4013.0	0.0334	

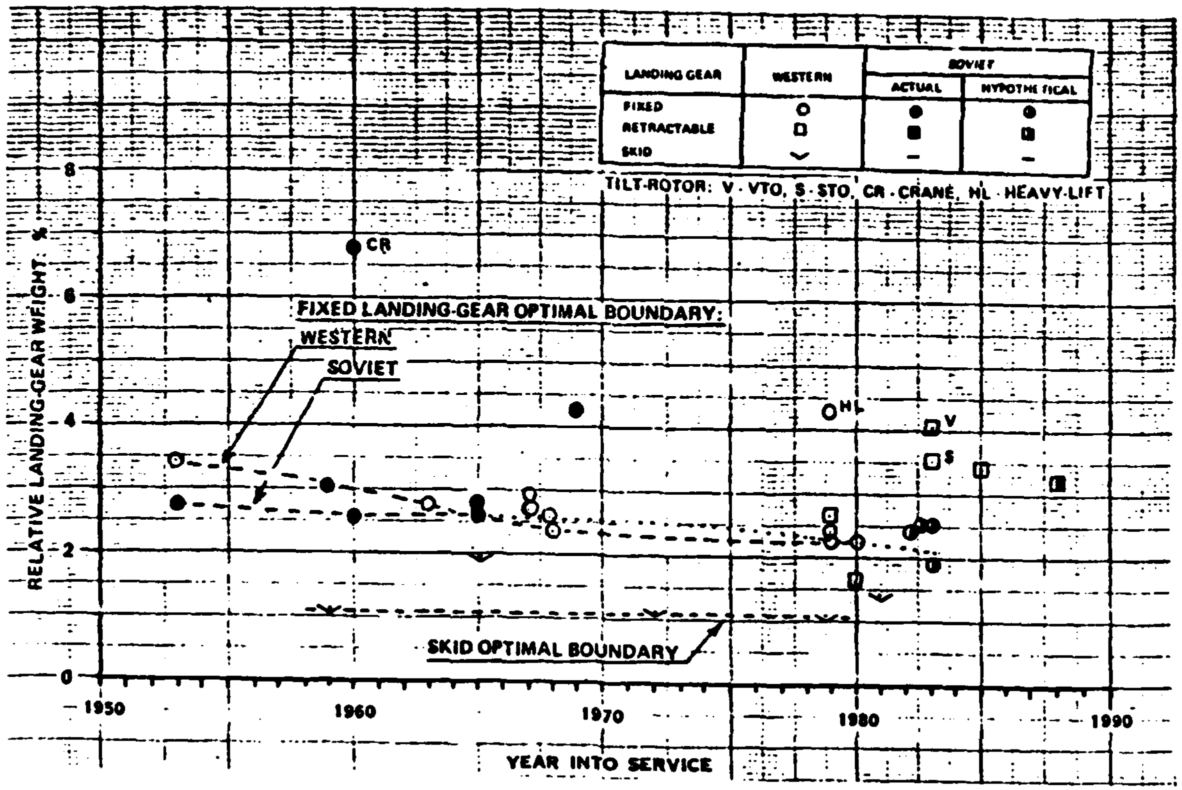


Figure 1.9 Temporal trends in relative weights of landing gears

slight decline with time in the $\overline{W}_{lg}$ value can also be depicted in Soviet designs. Special tall landing gears for a crane helicopter obviously results in a much higher $\overline{W}_{lg}$ level than for normal undercarriages. One also should note that the relative weights of Soviet fixed landing gears are generally quite close to those of their Western counterparts. With respect to Soviet retractable landing gears, one of the points shown in Fig. 1.9 represents the $\overline{W}_{lg}$ value for a hypothetical helicopter[4]. The anticipated $\overline{W}_{lg}$ level appears similar to those of some Western rotorcraft.

1.6.3 Influence of Rotorcraft Size (W_{max}) on $\overline{W}_{lg}$ levels

The influence of rotorcraft maximum flying weight on $\overline{W}_{lg}$ values can be studied from Fig. 1.10. Looking at this figure, the following trends can be detected.

1. In the Western group, one will note that, in principle, the relative weight of the skid-type landing gear does not seem to be affected by W_{max} values. Also, $\overline{W}_{lg}$ levels for wheel-type fixed landing gears does not appear to be affected (in a trend manner) by the flying gross-weight values. Higher-than-normal $\overline{W}_{lg}$ values for the heavy-lift helicopter should be attributed to the specific configuration of its landing gear, and not its maximum flying gross weight. With respect to the retractable landing gear, there are not enough points at this time to establish a meaningful trend.

2. With respect to Soviet helicopters, a trend of almost constant $\overline{W}_{lg}$ values with W_{max} for fixed-whee[illegible]ype landing gears seems to emerge from an examination of Fig. 1.1C where the so-called optimal boundary also appear[illegible]present the average $\overline{W}_{lg} = f(W_{max})$ line. Extension of the optimal [illegible]dary using data for hypothetical helicopters[4] appears to support [illegible] trend of $\overline{W}_{lg}$ vs. W_{max} being almost constant. Similar to the case of Western heavy-lift helicopters, high values of the $\overline{W}_{lg}$ points representing the crane configuration and the Mil V-12 side-by-side helicopter are exceptions resulting from specific landing-gear configurations. There is simply no data available regarding retractable landing gears to establish a trend of $\overline{W}_{lg}$ vs. W_{max}. This is due to the fact that all presently operational helicopters have fixed landing gears and, except for a single point, this investigator could not find any $\overline{W}_{lg}$ values for retractable landing gears of hypothetical helicopters.

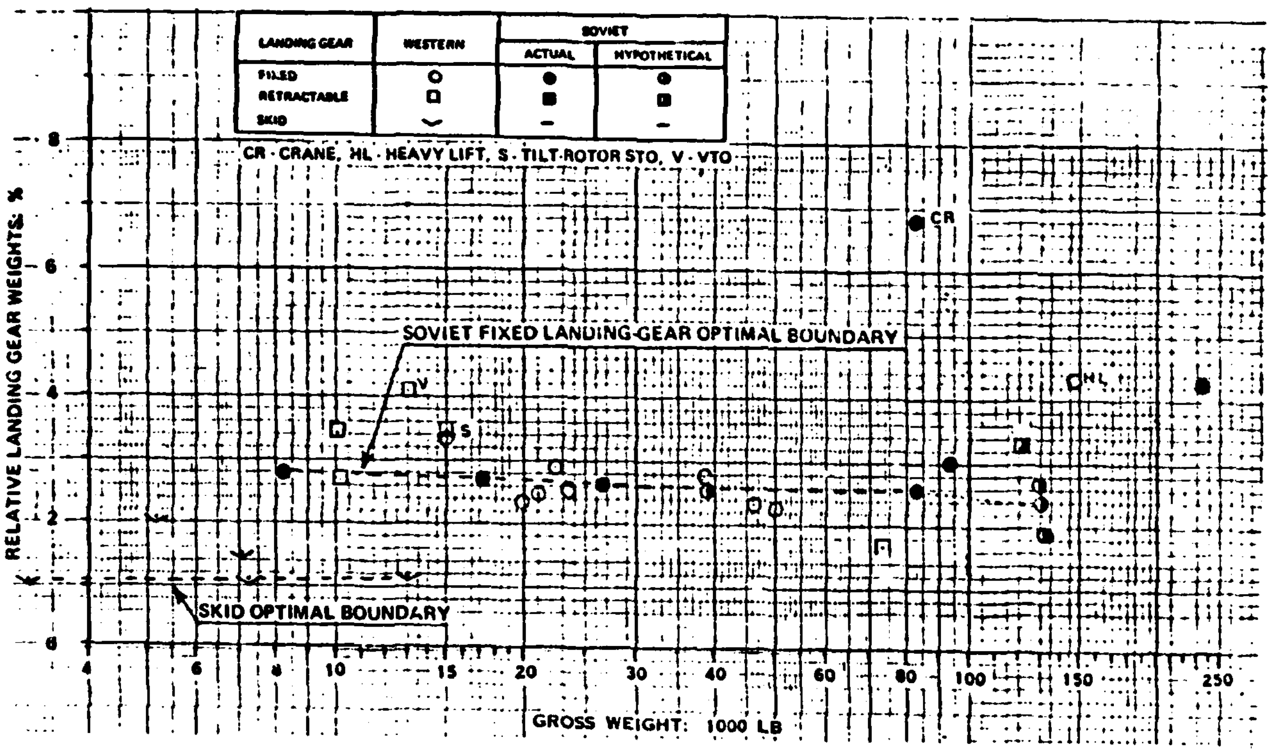


Figure 10. Trends of relative landing-gear weights vs. rotorcraft size (max. flying gross weight)

1.7 Trends in Relative Weights of the Drive System

1.7.1 General

In weight predictions of the drive system, separate estimates are usually made for gearboxes and shafts. Furthermore, it may be anticipated that one of the main factors determining the weight of the drive system will be the magnitude of torque transmitted through various elements of the system. Consequently, such characteristics as power installed and overall transmission ratio would more strongly affect the drive-system weight level than the size of a rotorcraft expressed through its maximum flying gross weight. The influence of power and transmission ratio on transmission weight will be discussed at the end of this section. However, since the present study is aimed at presenting the influence of relative weights of major rotorcraft components on relative weight empty, the same philosophy will be maintained. Consequently, with respect to weight, the drive system will be treated as a single whole, and its relative weight ($\overline{W}_{ds}$) will be related, as in preceding cases, to the maximum flying weight of the rotorcraft. Thus,

$$\overline{W}_{ds} = W_{ds}/W_{max}. \tag{1.6}$$

Also as in the past, both temporal and size-related (W_{max}) rotorcraft trends in the $\overline{W}_{ds}$ values will be examined. Basic data required for establishing these trends are given in Table 1.6.

1.7.2 Temporal Trends in $\overline{W}_{ds}$ Ratios

Temporal variations in relative drive-system weight are presented in Fig. 1.11, from which the following trends will be deduced.

With respect to Western rotorcraft, one would note that for pure helicopters, the scatter in $\overline{W}_{ds}$ values is not as high as anticipated. Furthermore, looking at the optimal boundary, one may assume that there exists some potential trend toward reduction of the relative drive-system weight with time, in spite of a definite tendency to install more power per pound of helicopter gross weight and even in the cases of establishing operational power limits to have more power available per pound of gross weight in the newer aircraft.

It should be emphasized, however, that the potential trend toward decreasing $\overline{W}_{ds}$ values with time is slight, and when one looks at the trend represented by average $\overline{W}_{ds}$ values, it appears almost constant, staying at about an 8% level throughout the years.

For the tilt rotor configuration — as represented by the XV-15 — the $\overline{W}_{ds}$ values are higher (especially for VTO operations) than for corresponding helicopters.

Soviet helicopters generally exhibit trends similar to those of their Western counterparts. Their optimal boundary for existing machines runs very close to that of the West. A tentative extension of that boundary on the basis of data for Soviet hypotheticals also remains close to Western projections. There is also a similarity in the scatter of points for the two design schools. Looking at the projections as represented by the hypothetical helicopters, one would note that the Soviets anticipate (contrary to the actual Western trend) considerably higher $\overline{W}_{ds}$ values for the large (52 metric-ton) tandem helicopter. This aspect will be more clearly visible in Fig. 1.12.

TABLE 16

RELATIVE DRIVE-SYSTEM WEIGHT ESTIMATES

DATA SHEET - WESTERN HELICOPTERS

MFGR	MODEL	YEAR	MAX FLYING WT	DRIVE-SYSTEM WT	REL. WT	
Aerospatiale	SA-330J	1978	16315			
Aerospatiale	SA-365N	1981	8618			
Aerospatiale	AS-332L	1981	18410			
Aerospatiale	365	1982	8928			
Agusta	A-109A	1975	5732			
Agusta/Sikorsky	AS-61N1	1984	22000			
Bell	UH-1A	1959	7200	526.0	0.0730	
Bell	UH-1B	1961	8500			
Bell	UH-1C M	1963	9500			
Bell	AH-1G	1967	9500			
Bell	UH-1N	1970	11200			
Bell	214A	1972	13000	989.0	0.0761	
Bell	OH-58C	1978	3200	186.0	0.0581	
Bell	412	1981	11900			
Bell	214ST	1982	17500			
Bell	XV-15	1983	15000	1333.0	0.0889	STO
	XV-15	1983	13000	1333.0	0.1025	VTO
Bell/Boeing	V-22	1990+	55000			
Bell/Boeing	V-22	1990	47500			
Boeing Vertol	CH-47A	1963	38550	3531.0	0.0916	
Boeing Vertol	CH-47A	1963	33000	3531.0	0.1070	
Boeing Vertol	CH-46A	1964	21400			
Boeing Vertol	CH-46E	1966	23300			
Boeing Vertol	CH-47B	1967	40000	3526.0	0.0881	
Boeing Vertol	CH-46F	1968	23300	1596.0	0.0685	
Boeing Vertol	CH-47C	1968	46000	3665.0	0.0797	
Boeing Vertol	XCH-62A	1979	148000	10336.0	0.0698	
Boeing Vertol	YUH-61A	1979	19700	1794.0	0.0911	
Boeing Vertol	CH-47D	1980	50000	4296.0	0.0858	
Boeing Vertol	234LR	1981	48500			
Eurofar	Hypo.	1998	28665			
Eurofar	Hypo.	1998	22491			
McDonnell-Douglas	500E	1982	3550			
McDonnell-Douglas	AH-64A	1983	21000	1342.0	0.0639	
MBB	BO105CB	1966	5114	435.9	0.0852	
MBB/Kawasaki	BK-117A-3	1981	7055	516.0	0.0731	
Piasecki	HUP-2	1951	6100			
Piasecki	HUP-4	1953	5740			
Piasecki	H-21C	1951	15000	1227.0	0.0818	
Piasecki	YH-16A	1955	38000			
Sikorsky	H-34A	1955	13300			
Sikorsky	H-37A	1955	31000			
Sikorsky	S-61A	1961	21500			
Sikorsky	S-61L	1961	19000			
Sikorsky	CH-54A	1964	42000			
Sikorsky	CH-3C	1964	22050			
Sikorsky	CH-54B	1966	42000			
Sikorsky	CH-53A	1966	46000			
Lockheed	AH-56A	1968	22550	1680.0	0.0745	
Sikorsky	CH-53D	1969	42000			
Sikorsky	S-64E	1969	42000			
Sikorsky	S-76	1979	10300	748.0	0.0726	
Sikorsky	UH-60A	1979	20250	1456.0	0.0719	
Sikorsky	CH-53E	1980	73500	6257.0	0.0851	
Sikorsky	S-75	1985	10000	769.0	0.0769	
Sud Aviation	SA-321	1966	26455			
Westland	WG-13	1972	9500			
Westland	Lynx	1977	10000			
Westland	WG-30	1982	12250			

RELATIVE DRIVE SYSTEM WEIGHT ESTIMATES (CONT'D)

DATA SHEET - RUSSIAN HELICOPTERS

MFGR	MODEL	YEAR	MAX FLYING WT	DRIVE-SYSTEM WT	REL. WT	COMMENTS
USSR	MI-1	1951	4950	415.0	0.0837	
USSR	MI-2	1965	8175	750.2	0.0918	
USSR	MI-4	1953	17200	1726.2	0.0759	
USSR	MI-6	1957	93700	8410.2	0.0898	2 X 5500 hp
USSR	MI-6	1963	93700	8471.6	0.0904	2 X 6650 hp
USSR	MI-8	1965	26450	1987.3	0.0751	
USSR	MI-10	1960	82775			
USSR	MI-14	1973	30865			
USSR	MI-17	1982	29660			
USSR	MI-24	1973	24250			
USSR	MI-26	1982	123480			
USSR	KA-25	1961	16160			
USSR	KA-26	1970	7165			
USSR	KA-25A	1967	16100			
USSR	V-12	1969	231500	[16127.4]	[0.0696]	
Tishchenko	SRS-52	1983	129210	11290.0	0.0874	
Tishchenko	SR-15	1983	38760	2723.2	0.0703	
Tishchenko	SR-24	1983	60100			
Tishchenko	SR-52	1983	131375	12017.0	0.0915	
Tishchenko	TA-15	1983	38500	3162.0	0.0821	
Tishchenko	TA-52	1983	130000	14332.5	0.1102	

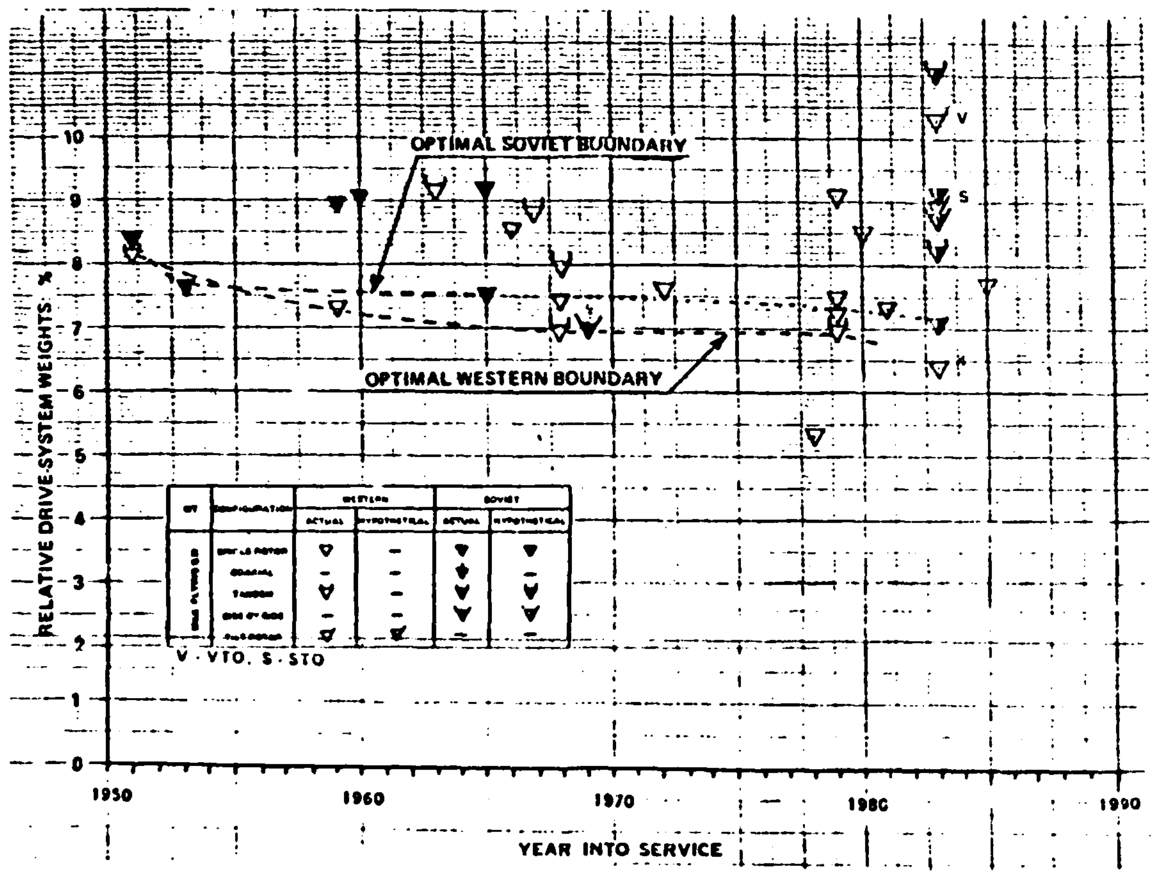


Figure 1.11 Temporal trends in relative weights of drive systems

1.7.3 $\overline{W}_{ds}$ Trends with Respect to Maximum Gross Weight

Relative weights of the drive system — as defined by Eq. (6) — are plotted vs. maximum flying gross weight in Fig. 1.12. Examination of this figure would suggest the following trends.

Should one sketch an optimal boundary for Western rotorcraft, it would show that no definite trend appears in the $\overline{W}_{ds} = f(W_{max})$ relationship. Furthermore, looking at the distribution of the average $\overline{W}_{ds}$ values, one would get the impression that — similar to the temporal trend, the $\overline{W}_{ds}$ level remains, on the average, almost constant with respect to W_{max} (equal to about 8 percent). The trend indicated in the previous figure is confirmed here with respect to the tilt-rotor representation; namely, showing that the $\overline{W}_{ds}$ value, especially in the VTO case, is higher than that for helicopters of the same weight class.

With respect to Soviet helicopters, it was not possible to establish a clearly defined optimal boundary. Looking at the hypothetical helicopters, it is interesting to note that with the exception of the single-rotor 15 metric-ton class, the authors of Ref. 4 do not visualize any reductions in $\overline{W}_{ds}$ values below traditional levels. Furthermore, for the 52-ton tandem configuration, they visualize relative drive-system weights higher than those for the single-rotor or side-by-side helicopters of the same weight class, and considerably higher than for the Western tandem heavy-lift helicopter (CH-62A).

1.7.4 Some Other Ways of Relating Drive-System Weights to Rotorcraft Characteristics

In order to determine whether the scatter visible in Figs. 1.11 and 1.12 may be reduced, as well as to single out factors which may contribute to a future reduction in system weight, the relationship of the drive-system weight to other principal rotorcraft characteristics is investigated. Thus, in Fig. 1.13, the drive-system weight divided by transmission rating (P) is plotted for Western helicopters vs. year introduced into service.

A glance at this figure would suggest the following temporal trend in transmission weight per horsepower of transmission rating. The shape of the optimal boundary seems to indicate a rapid decrease in W_{ds}/P values in the 1950-1960 time period, and then leveling off. This trend also appears to be confirmed by the overall distribution of points, which also indicates that in the 1960-1980+ time period, the average drive-system weight per hp of transmission rating remains practically constant at the $W_{ds}/P \approx 0.055$ lb/hp level.

A different method was used to relate drive-system weight to other major helicopter characteristics through the following parameter (κ):

$$\kappa = W_{ds}/W_{max}\sqrt{w}, \qquad (1.7)$$

where W_{max} is the helicopter maximum flying weight in pounds and w is the corresponding main-rotor(s) disc-loading in psf.

The selection of $W_{max}\sqrt{w}$ as the denominator in Eq. (1.7) was supported by the following reasoning.

In hover, the rotor horsepower can be expressed as

$$RHP_h = T^{3/2}/550FM\sqrt{2\rho A} \qquad (1.8)$$

where T is the total rotor thrust, FM is the rotor figure of merit, ρ is the air density, and A is the rotor(s) area.

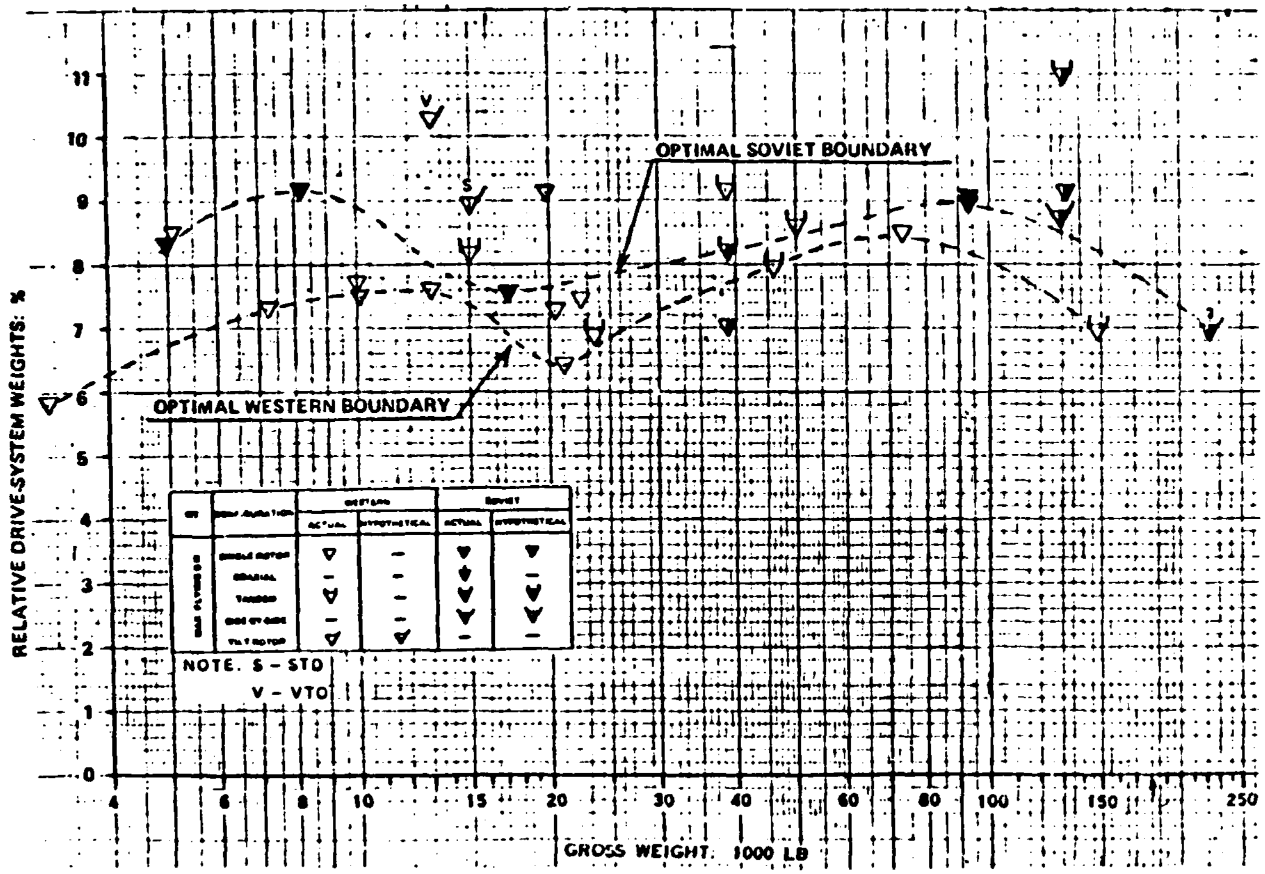


Figure 1.12 Relative weight trends of drive system vs. gross weight

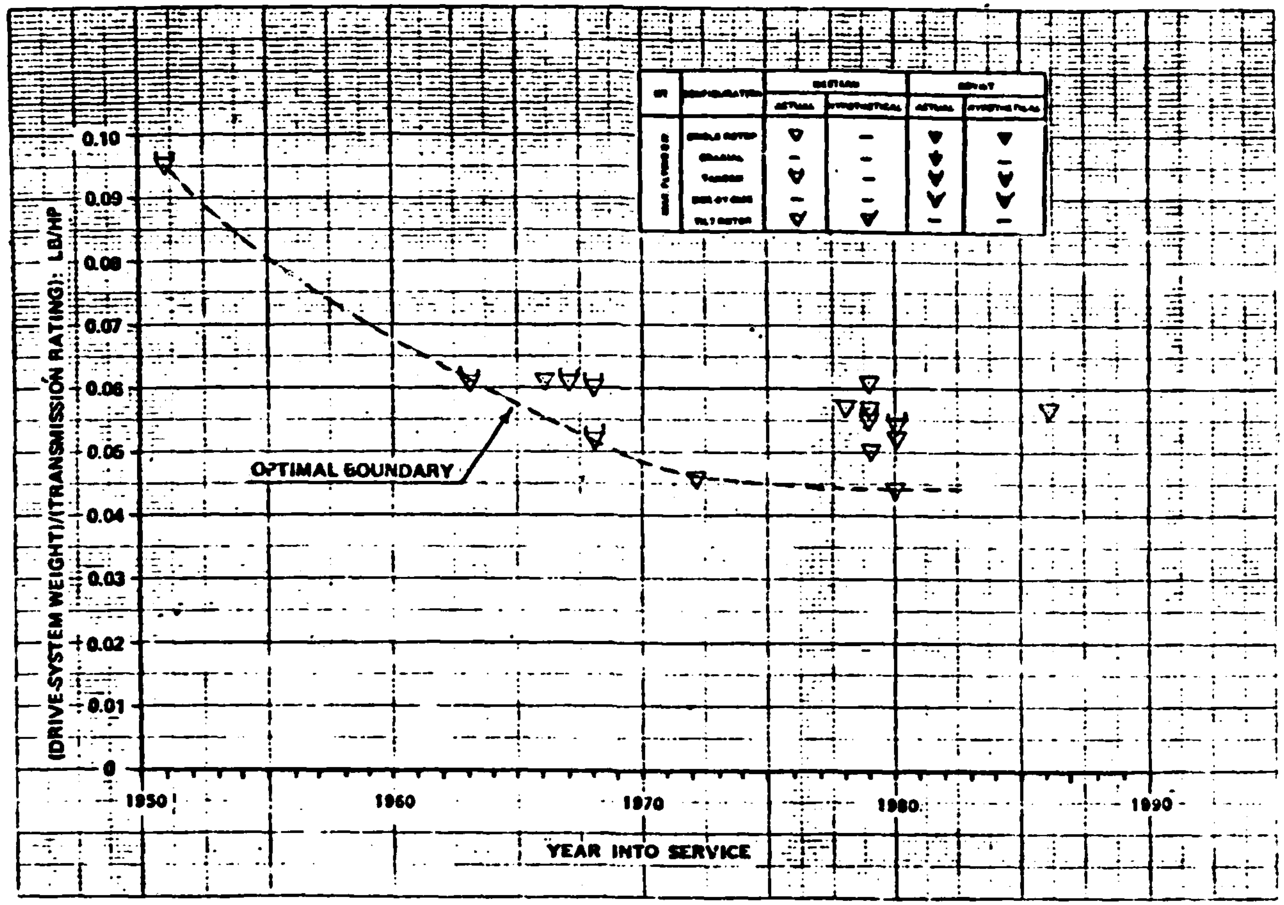


Figure 1.13 Temporal trends in drive-system weights per horsepower of transmission rating

It can be seen from Eq. (1.8) that

$$RHP_h = f(W^{3/2}/\sqrt{A}).$$

This, in turn, can be rewritten as

$$RHP_h = f(W\sqrt{w}). \tag{1.9}$$

As in the preceding case, κ values for Western helicopters were plotted vs. year of entering service in Fig. 1.14. Looking at this figure, the following temporal trend in κ levels seem to emerge. On the average, κ appears to remain almost constant, and approximately equal to 0.0130 lb/lb$\sqrt{\text{psf}}$. The shape of the optimal boundary suggests the potential for a slight decline in κ values with years.

From the interpretation of Figures 1.11, 1.13, and 1.14, one may conclude that there is a trend toward slightly lighter drive-systems with the passage of time, where the lightness is judged by (a) the level of the relative weight ($\overline{W}_{ds}$), (b) weight per hp of the transmission rating (W_{ds}/P), and (c) by the values of the κ parameter.

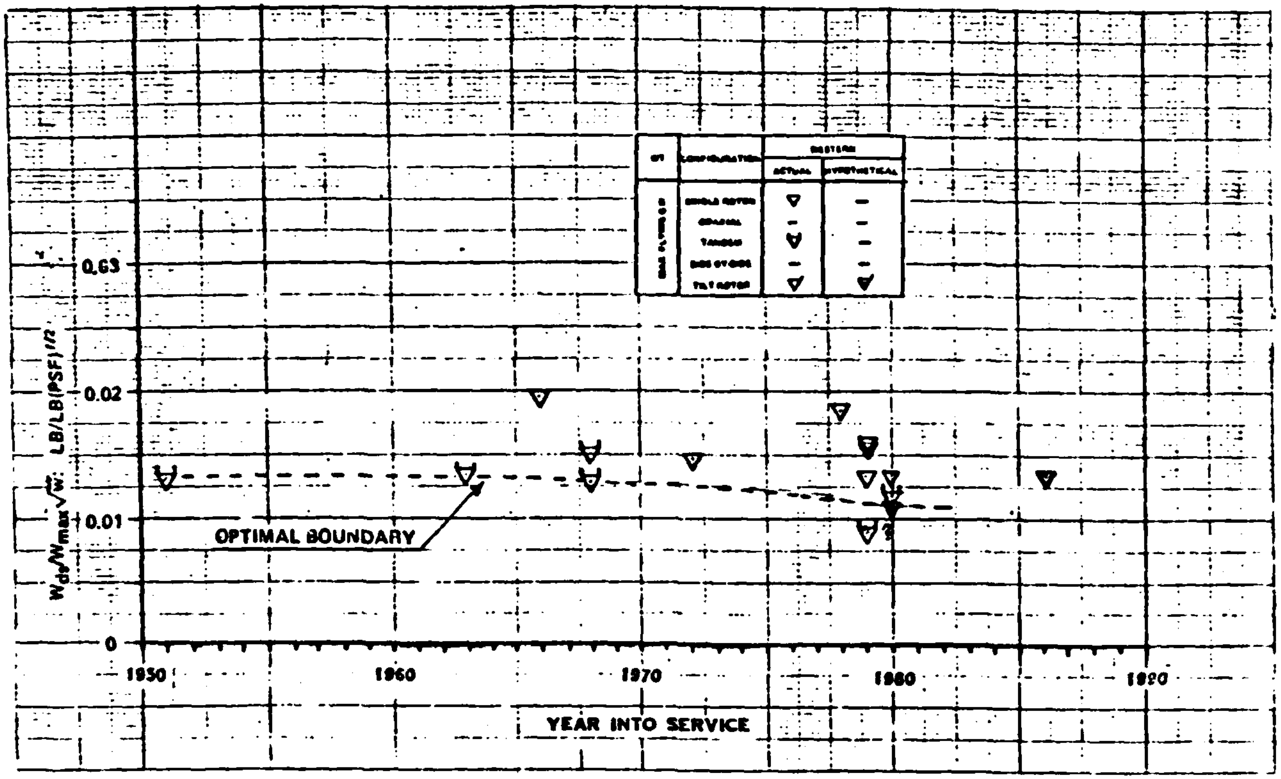


Figure 1.14 Temporal trends in the $W_{ds}/W_{max}\sqrt{w}$ parameter for Western helicopters

1.8 Trends in Relative Weights of Fuel System

1.8.1 General

In weight-prediction methods, the weight of the fuel system is usually directly related to the fuel capacity of the aircraft. Furthermore, it may be expected that the weight of this system would be strongly affected by such factors as self-sealing and crash-resistant requirements. For this reason, it may be anticipated that a large scatter would be encountered if one relates the fuel-system weight to aircraft gross weight. Nevertheless, this latter approach will also be used here. Thus, for reasons already discussed in the preceding section, the relative weight of the fuel system ($\bar{W}_{fs}$) is defined as

$$\bar{W}_{fs} = W_{fs}/W_{max}. \tag{1.10}$$

It should also be noted that because on the average, $(\bar{W}_{fs})_{av} \approx 1.6\%$ (see Table 3.8[1]), changes in $\bar{W}_{fs}$ values would have only a secondary effect on the rotorcraft weight-empty level when compared with the influence of relative weights of other major components. For this reason, only a brief examination of gross weight-related trends is performed here. Basic inputs for this task are given in Table 1.7.

1.8.2 Temporal Trends in $\bar{W}_{fs}$

Even though the data shown in Figure 1.15 is somewhat limited, looking at this figure one would note that for Western helicopters there is, as anticipated, a large scatter of $\bar{W}_{fs}$ values. Further insight would indicate that these higher $\bar{W}_{fs}$ values (as high as 2.10%) represent military helicopters, where crash-resistant and self-sealing requirements are applied, while the optimal boundary remains practically constant vs. time, remaining at about the 1.1% level.

With respect to Soviet helicopters, one would note that their optimal $\bar{W}_{fs}$ boundary stays very close to its Western counterpart until the mid-sixties and then dips below it with future projections to a low level of $\bar{W}_{fs} \approx 0.8\%$ only. For relative fuel-system weights, the general scatter of the actual and hypothetical helicopters is comparatively low. In that respect, it would be interesting to obtain data for their combat-type helicopters, where self-sealing and crash-resistant requirements are probably incorporated, and see how their $\bar{W}_{fs}$ values would fit into the general trend picture of Fig. 1.15.

1.8.3 Influence of Rotorcraft Size on $\bar{W}_{fs}$ Level

A glance at Fig. 1.16 will indicate that for Western helicopters, there appears to be no visible trend in the variations of $\bar{W}_{fs} = f(W_{max})$. A closer examination will show, as indicated in the preceding subsection, that the $\bar{W}_{fs}$ value is primarily influenced by crash-resistant and self-sealing requirements, and not by the helicopter size.

As to Soviet helicopters for which there is apparently no crash-resistant and self-sealing requirements, ordinates of the optimal boundary remain practically constant throughout the weight range, and $\bar{W}_{fs}$ values for other points do not excessively deviate from the optimum.

TABLE 1.7

RELATIVE FUEL-SYSTEM WEIGHT ESTIMATES

DATA SHEET - WESTERN HELICOPTERS

MFGR	MODEL	YEAR	MAX FLYING WT	FUEL-SYSTEM WT	REL. WT	COMMENTS
Aerospatiale	SA-330J	1978	16315			
Aerospatiale	SA-365N	1981	6818			
Aerospatiale	AS-332L	1981	18410			
Aerospatiale	365	1982	8928			
Agusta	A-109A	1976	5732			
Agusta/Sikorsky	AS-61N1	1984	22000			
Bell	UH-1A	1959	7200			
Bell	UH-1B	1961	8500			
Bell	UH-1D/H	1963	9500			
Bell	AH-1G	1967	9500			
Bell	UH-1N	1970	11200			
Bell	214A	1972	13000			
Bell	OH-58C	1978	3200			
Bell	412	1981	11900			
Bell	214ST	1982	17500			
Bell	XV-15	1963	15000			
Bell	XV-15	1983	13000			
Bell/Boeing	V-22	1990*	55000			
Bell/Boeing	V-22	1990	47500			
Boeing Vertol	CH-47A	1963	38550	440.0	0.0114	Self-Sealing
Boeing Vertol	CH-47A	1963	33000	440.0	0.0133	
Boeing Vertol	CH-46A	1964	21400			
Boeing Vertol	CH-46E	1966	23300			
Boeing Vertol	CH-47B	1967	40000	730.0	0.0182	Protected Tank
Boeing Vertol	CH-46F	1968	23300			
Boeing Vertol	CH-47C	1968	46000	1131.0	0.0246	
Boeing Vertol	XCH-62A	1979	148000			
Boeing Vertol	YUH-61A	1979	19700			
Boeing Vertol	CH-47D	1980	50000			
Boeing Vertol	234LR	1981	48500			
Eurofar	Hypo.	1990	28665			
Eurofar	Hypo.	1990	22491			
McDonnell-Douglas	500E	1982	3550			
McDonnell-Douglas	AH-64A	1983	21000			
MBB	BO105C/D	1966	5114	67.6	0.0132	
MBB/Kawasaki	BK-117A-3	1981	7055	77.2	0.0109	
Piasecki	HUP-2	1951	6100			
Piasecki	HUP-4	1953	5740			
Piasecki	H-21C	1951	15000	1167.2	0.0111	
Piasecki	YH-16A	1955	38000			
Sikorsky	H-34A	1955	13300			
Sikorsky	H-37A	1955	31000			
Sikorsky	S-61A	1961	21500			
Sikorsky	S-61L	1961	19000			
Sikorsky	CH-54A	1964	42000			
Sikorsky	CH-3C	1964	22050			
Sikorsky	CH-54B	1966	42000			
Sikorsky	CH-53A	1966	40000			
Lockheed	AH-56A	1968	22550			
Sikorsky	CH-53D	1969	42000			
Sikorsky	S-64E	1969	42000			
Sikorsky	S-76	1979	10300			
Sikorsky	UH-60A	1979	20250	429.1	0.0212	Crash Resistant, Self-Sealing Tanks
Sikorsky	CH-53E	1980	73500	1225.0	0.0167	
Sikorsky	S-75	1985	10000			
Sud Aviation	SA-321	1966	26455			
Westland	WG-13	1972	9500			
Westland	Lynx	1977	10000			
Westland	30 (?)	1982	12350			

RELATIVE FUEL-SYSTEM WEIGHT ESTIMATES (CONT'D)

DATA SHEET - SOVIET HELICOPTERS

MFGR	MODEL	YEAR	MAX FLYING WT	FUEL-SYSTEM WT	REL. WT	COMMENTS
USSR	MI-1	1951	4960	48.4	0.0098	
USSR	MI-2	1965	8175	79.9	0.0098	
USSR	MI-4	1952	17200	172.2	0.0100	
USSR	MI-6	1959	93700	1180.8	0.0126	
USSR	MI-8	1965	26450	361.3	0.0137	
USSR	MI-10	1960	83775	1298.3	0.0155	
USSR	MI-14	1973	30865			
USSR	MI-17	1982	28660			
USSR	MI-24	1973	24250			
USSR	MI-26	1982	123480			
USSR	KA-25	1961	16100			
USSR	KA-26	1970	7165			
USSR	KA-25K	1967	16100			
USSR	V-12	1969	231500	1681.5	0.0073	
Tishchenkoe	SBS-52	1983	129210	1764.0	0.0137	
Tishchenko	SR-15	1983	38760	286.7	0.0074	
Tishchenko	SR-24	1983	60100			
Tishchenko	SR-52	1983	131375	1720.0	0.0131	
Tishchenko	TA-15	1983	38500	29[illegible].7	0.0077	
Tishchenko	TA-52	1983	130000	1653.8	0.0127	

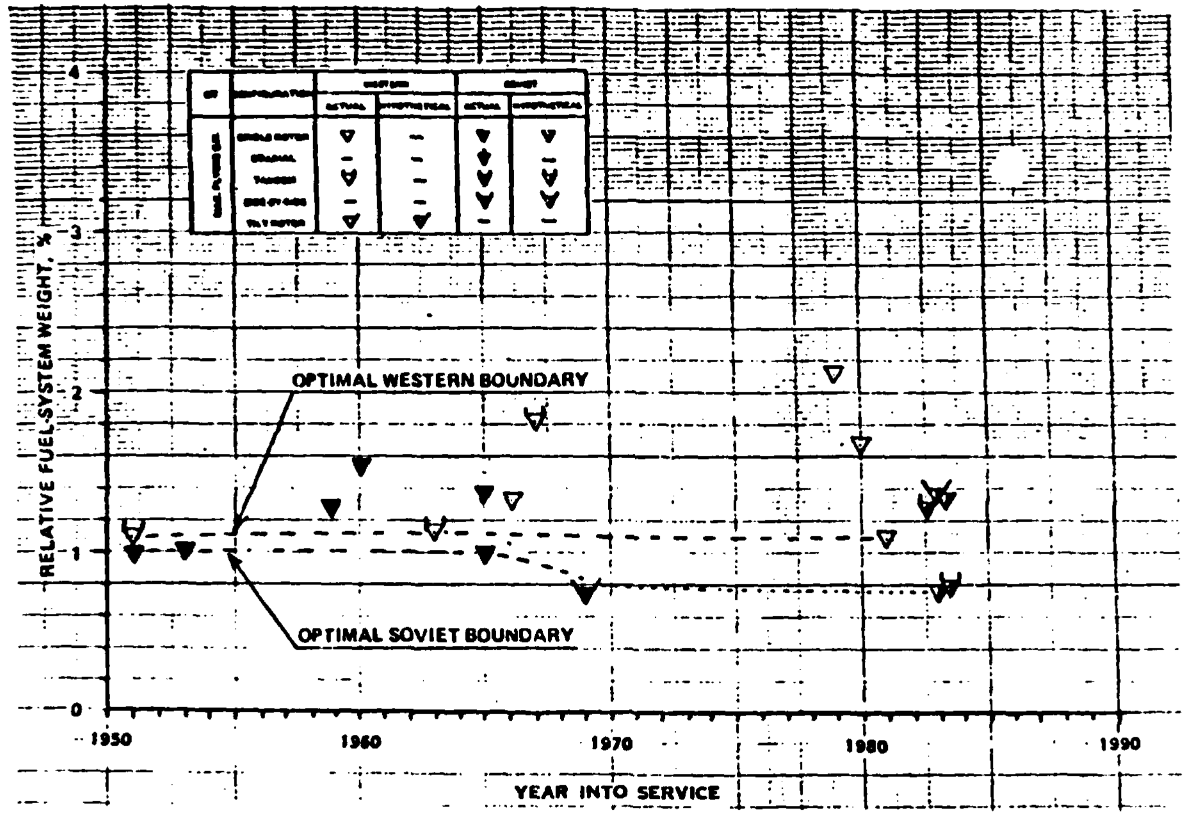


Figure 1.15 Temporal trends in relative fuel-system weights

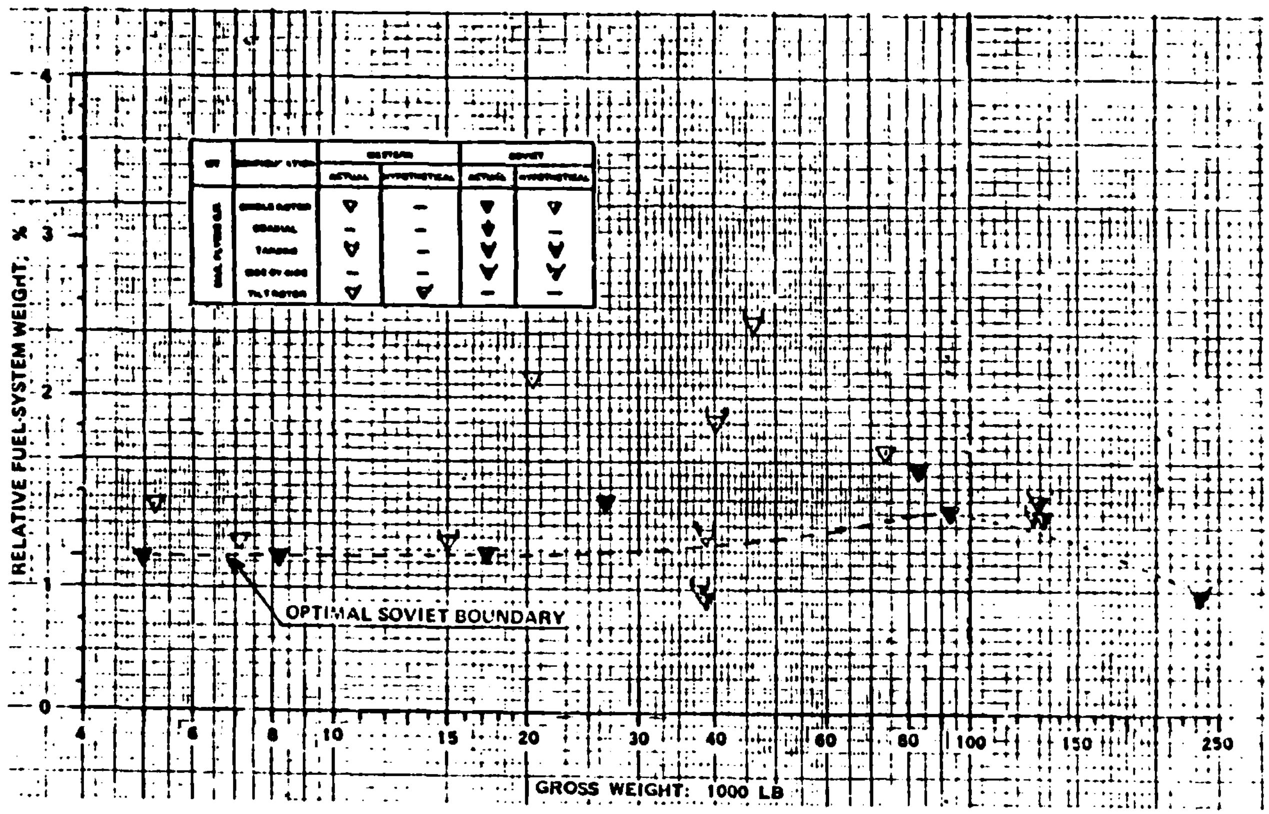


Figure 1.16 Relative fuel-system weight vs. gross weight

1.9 Trends in Relative Weights of Flight Control Group

1.9.1 General

Similar to the case of the drive system in the weight-prediction procedure, separate estimates are usually made for the cockpit and the remaining controls including the boosting systems. However, here again, as in Section 1.7, only the overall weights of flight controls will be considered and, as usual, the relative weight of this major rotorcraft component is defined as

$$\overline{W}_{fc} = W_{fc}/W_{max}. \qquad (1.11)$$

The basic data required for establishing temporal and rotorcraft size related (based on maximum flying gross weight) trends in $\overline{W}_{fc}$ variations are presented in Table 1.8.

1.9.2 Temporal Trends in $\overline{W}_{fc}$ Ratios

Relative weights of the flight-control group of both Western rotorcraft and Soviet helicopters are shown vs. year of introduction into service in Fig. 1.17. Looking at this figure, the following trends appear to emerge.

The optimal boundary for Western helicopters suggests a potential for reduction of $\overline{W}_{fc}$ values with the progress of time. However, when one examines the overall distribution of the relative weight points, it becomes clear that the temporal decrease in the $\overline{W}_{fc}$ level was, on the average, much smaller than could be anticipated from the optimal trend. With respect to the tilt-rotor as represented by the XV-15, it is quite clear that because of the presence of rotor-attitude controls, one may expect much higher $\overline{W}_{fc}$ values than for conventional helicopters.

With respect to Soviet helicopters, one would note that the temporal trend is similar to that of their Western counterparts. For instance, the Soviet optimal boundary — extended toward $\overline{W}_{fc}$ values for hypothetical helicopters — seems to indicate both an actual trend and probably a conscious effort at present as well as in the future toward reduction of the relative weight of flight controls. It also appears that in spite of a high $\overline{W}_{fc}$ level for the existing side-by-side helicopter (Mil V-12), they hope that in the future the relative weight of flight controls for the side-by-side configurations can be kept basically on the same level as for the single-rotor configuration.

1.9.3 $\overline{W}_{fc}$ Trends on Maximum Gross Weights

Relative weights of the flight-control group vs. W_{max} of both Western rotorcraft and Soviet helicopters are shown in Fig. 1.18, where the following trends seem to emerge.

With respect to Western helicopters, once the points representing helicopters with little boosting are excluded, there appears to be little change in the optimal boundary as a function of the W_{max} values, staying close to the $\overline{W}_{fc} \approx 4\%$ level. The overall distribution of the $\overline{W}_{fc}$ points as well does not lead to a detection of any clear pattern of the variation in the relative weight of the flight controls with respect to W_{max}. Points representing the tilt-rotor rotorcraft indicate that, as already pointed out in the preceding subsection, the $\overline{W}_{fc}$ values for this configuration are more than two times higher than for helicopters of the same weight class.

TABLE 1.8

RELATIVE FLIGHT-CONTROL GROUP WEIGHT ESTIMATES

DATA SHEET - WESTERN HELICOPTERS

MFGR	MODEL	YEAR	MAX FLYING WT	FLT-CONTROL GRP.	REL. WT	COMMENTS
Aerospatiale	SA-332	1978	18[illegible]			
Aerospatiale	SA-365N	1981	8816			
Aerospatiale	AS-332L	1981	18[illegible]			
Aerospatiale	365	1982	8928			
Agusta	A-129	197[illegible]	5[illegible]			
Agusta/Sikorsky	AS-61	1[illegible]	2[illegible]			
Bell	UH-1A	19[illegible]	[illegible]			
Bell	UH-1B	1961	8500			
Bell	UH-1D	1963	9500			
Bell	AH-1G	1967	9500			
Bell	UH-1N	1970	11200			
Bell	214A	1972	13000	503.0	0.0387	
Bell	OH-58C	1978	3200	137.0	0.0428	
Bell	412	1981	11900			
Bell	214ST	1982	17500			
Bell	XV-15	1983	15000	1406.0	0.0937	
Bell	XV-15	1983	13000			
Bell/Boeing	V-22	1990	55000			
Bell/Boeing	V-22	1990	47500			
Boeing Vertol	CH-47A	1963	38550	1417.0	0.0368	
Boeing Vertol	CH-47A	1963	33000	1417.0		
Boeing Vertol	CH-46A	1964	21400			
Boeing Vertol	CH-46E	1966	23300			
Boeing Vertol	CH-47B	1967	40000	1474.0	0.0368	
Boeing Vertol	CH-46F	1968	23300	82.2	0.0035	
Boeing Vertol	CH-47C	1968	46000	1637.0	0.0356	
Boeing Vertol	YCH-62A	1979	148000	3445.0	0.0271	
Boeing Vertol	YUH-61A	1979	19700	912.1	0.0463	
Boeing Vertol	CH-47D	1980	50000	1766.0	0.0353	
Boeing Vertol	234LR	1981	48500			
Eurofar	Hypo.	1998	28665			
Eurofar	Hypo.	1998	22491			
McDonnell-Douglas	500E	1982	3550			
McDonnell-Douglas	AH-64A	1983	21000	767.0	0.0365	
MBB	BO105C/D	1966	5110	217.9	0.0426	
MBB/Kawasaki	BK-117A-3	1981	7055	179.6	0.0255	
Piasecki	HUP-2	1951	6100			
Piasecki	HUP-4	1953	5740			
Piasecki	H-21C	1951	15000	331.0	0.0221	
Piasecki	YH-16A	1955	38000			
Sikorsky	H-34A	1955	13300			
Sikorsky	H-37A	1955	31000			
Sikorsky	S-61A	1961	21500			
Sikorsky	S-61L	1961	19300			
Sikorsky	CH-54A	1964	42000			
Sikorsky	CH-3C	1964	22050			
Sikorsky	CH-54B	1966	42000			
Sikorsky	CH-53A	1966	40000			
Lockheed	AH-56A	1968	22550	1021.0	0.0453	
Sikorsky	CH-53D	1969	42000			
Sikorsky	S-64E	1969	42000			
Sikorsky	S-76	1979	[illegible]	265.0	0.0[illegible]	
Sikorsky	UH-60A	1977	21250	449.0	0.0[illegible]	
Sikorsky	CH-53E	1980	73500	1861.0	0.0[illegible]	
Sikorsky	S-75	1985	[illegible]			
Sud Aviation	SA-321	1966	26455			
Westland	WG-13	1972	9500			
Westland	Lynx	1977	10000			
Westland	30-100	1982	12250			

RELATIVE FLIGHT–CONTROL GROUP WEIGHT ESTIMATES (CONT'D)

DATA SHEET - SOVIET HELICOPTERS

MFGR	MODEL	YEAR	MAX FLYING WT	FLT-CONTROL GRP	REL. WT	COMMENTS
USSR	MI-1	1951	4960			
USSR	MI-2	1965	8175	350.1	0.0428	
USSR	MI-4	1953	17200	850.3	0.0494	
USSR	MI-6	1959	93700	5479.6	0.0584	
USSR	MI-8	1965	26450	1068.6	0.0404	
USSR	MI-10	1960	83775			
USSR	MI-14	1973	30865			
USSR	MI-17	1982	26660			
USSR	MI-24	1973	24250			
USSR	MI-26	1982	123480			
USSR	KA-25	1961	16100			
USSR	KA-26	1970	7165			
USSR	KA-25A	1967	16100			
USSR	V-12	1969	231500	15799.0 (?)	0.0682 (?)	
Tishchenko*	SDS-52	1983	129210	3675.1	0.0284	
Tishchenko	SR-15	1983	38760	1342.8	0.0346	
Tishchenko	SR-24	1983	60100			
Tishchenko	SD-52	1983	131375	3638.3	0.0277	
Tishchenko	TA-15	1983	38500	1675.6	0.0435	
Tishchenko	TA-52	1983	130000	4410.0	0.0339	

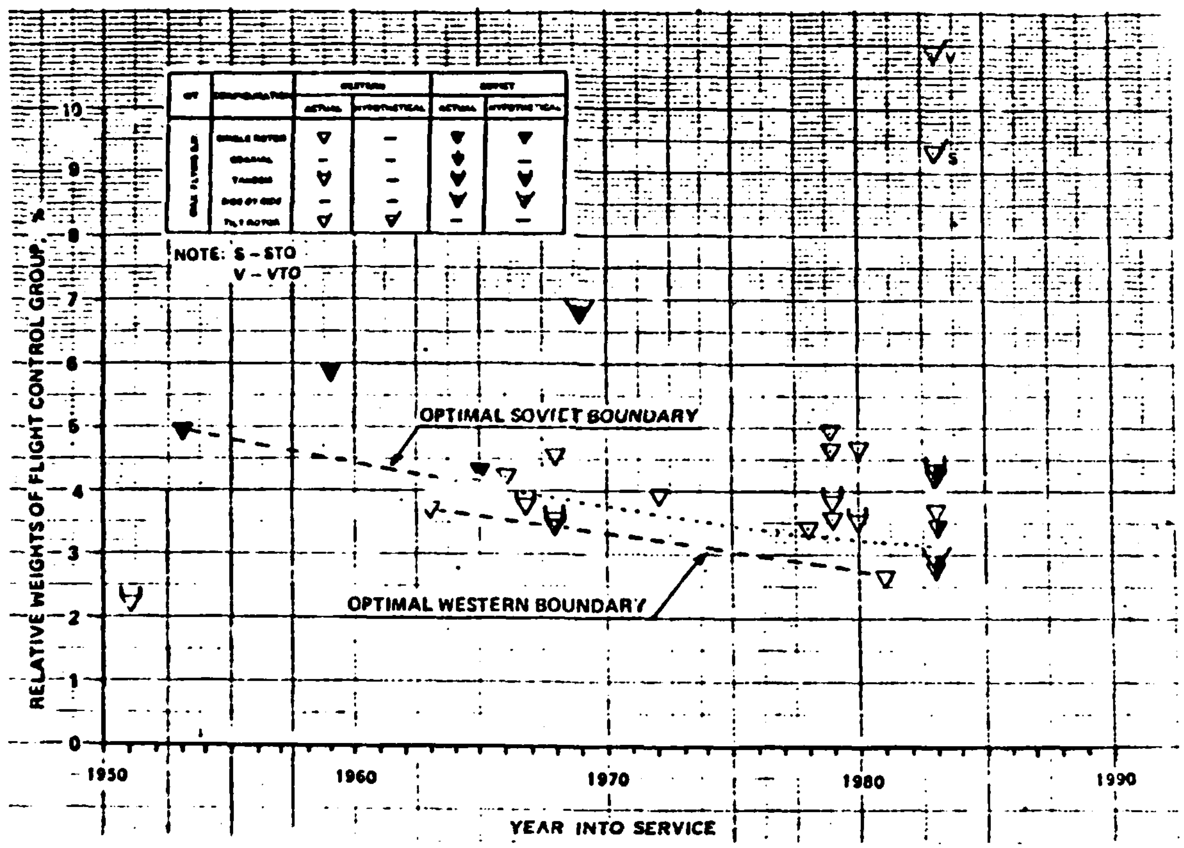


Figure 1.17 Temporal trends in relative flight-control group weights

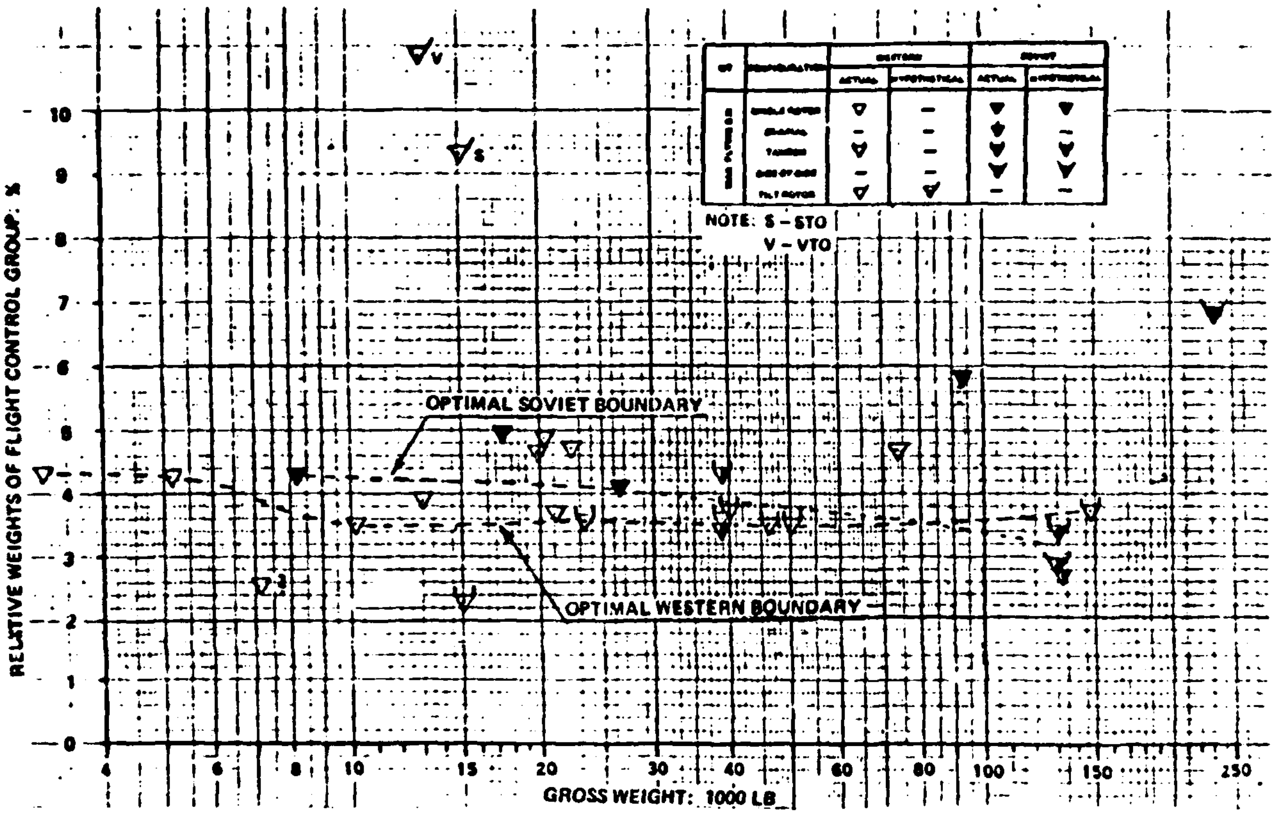


Figure 1.18 Relative weight trends of flight-control group vs. gross weight

For Soviet helicopters, the optimal boundary (extended toward hypothetical machines) also appears, as in the case of Western helicopters, close to the $\bar{W}_{fc} \approx 4\%$ value. As for future trends, only moderate reductions in relative weights of flight controls are expected. It is interesting to note that similar levels of $\bar{W}_{fc}$ values are projected for all configurations (single-rotor, side-by-side, and tandem), in spite of the fact that the actual relative weight of the flight controls of the Mil V-12 side-by-side helicopter is well above those for single-rotor types.

1.10 Discussion

1.10.1 Contributions of Major Component Weights to Rotorcraft Weight Empty

The relative weight-empty of a rotorcraft ($\overline{W}_e$) is obviously the sum of all the relative weights of major components:

$$\overline{W}_e = \overline{W}_{bl} + \overline{W}_h + \overline{W}_f + \overline{W}_{lg} + \overline{W}_{ds} + \overline{W}_{fs} + \overline{W}_{fc} + \overline{W}_{tr} + \overline{W}_{pss} + \overline{W}_{en} + \overline{W}_{fe}. \quad (1.12)$$

The first seven terms on the right side of Eq. (1.12) represent relative weights of components whose temporal and size-related (W_{max}) trends were discussed in this chapter. $\overline{W}_{tr}$ and $\overline{W}_{pss}$, respectively, are the relative weights of the tail-rotor group and propulsion subsystems, and the last two terms indicate the contribution of engines installed ($\overline{W}_{en}$) and fixed equipment ($\overline{W}_{fe}$).

Trends for $\overline{W}_{tr}$ and $\overline{W}_{pss}$ were not examined here because their contribution to the relative weight-empty is small.

The contribution of the engines(s) weight to weight-empty were quite considerable in the past; i.e., $\overline{W}_{en} \approx 0.094$ for the H-21C helicopter of the early fifties. At present, for helicopters, they have dropped to a much lower level; e.g., $\overline{W}_{en} \approx 0.033$ for the CH-47D. Consequently, further reductions in their relative weight values would only slightly influence the relative empty weight. However, for other rotorcraft configurations – for example, tilt-rotors – where the power installed per pound of maximum flying weight is considerably higher than for helicopters of the same gross-weight class, the role of $\overline{W}_{en}$ in achieving a certain level of the relative weight-empty may be more important. However, examination of the influence of new materials on the specific engine weight is beyond the limits of this study.

Fixed equipment (as in the past) represents an important contribution to rotorcraft weight-empty as depicted by $\overline{W}_{fe} \approx 0.075$ for the H-21C, and $\overline{W}_{fe} \approx 0.074$ for the CH-47D. It is obvious, hence, that a reduction in $\overline{W}_{fe}$ values may represent a significant factor in reducing the relative weight-empty levels. However, an investigation of possible reductions in $\overline{W}_{fe}$ values is also outside the scope of this study, especially in view of the fact that customer requirements probably has a stronger influence on the amount and type, and thus, the weight of the fixed equipment than any other requirement. Some of these aspects will be briefly discussed later.

Figure 1.19 was prepared in order to permit the reader to ascertain at a glance the importance of various major component weights regarding their contribution to weight-empty and, thus, to determine where the largest payoffs in reducing $\overline{W}_e$ levels can be achieved through the use of new materials. Here, relative weights representing the contemporary state of the art for the seven major helicopter components discussed in this chapter are shown in the order of their decreasing values. The representative relative major component weights were determined by computing their average values for the Western helicopters appearing within the 1980 ± 5 limits in figures showing temporal trends in the relative weights of components. The relative component weight values corresponding to the optimal boundary in the eighties are also marked in this figure. This should give the reader some idea as to the already existing possibilities of reducing the relative weights of these components.

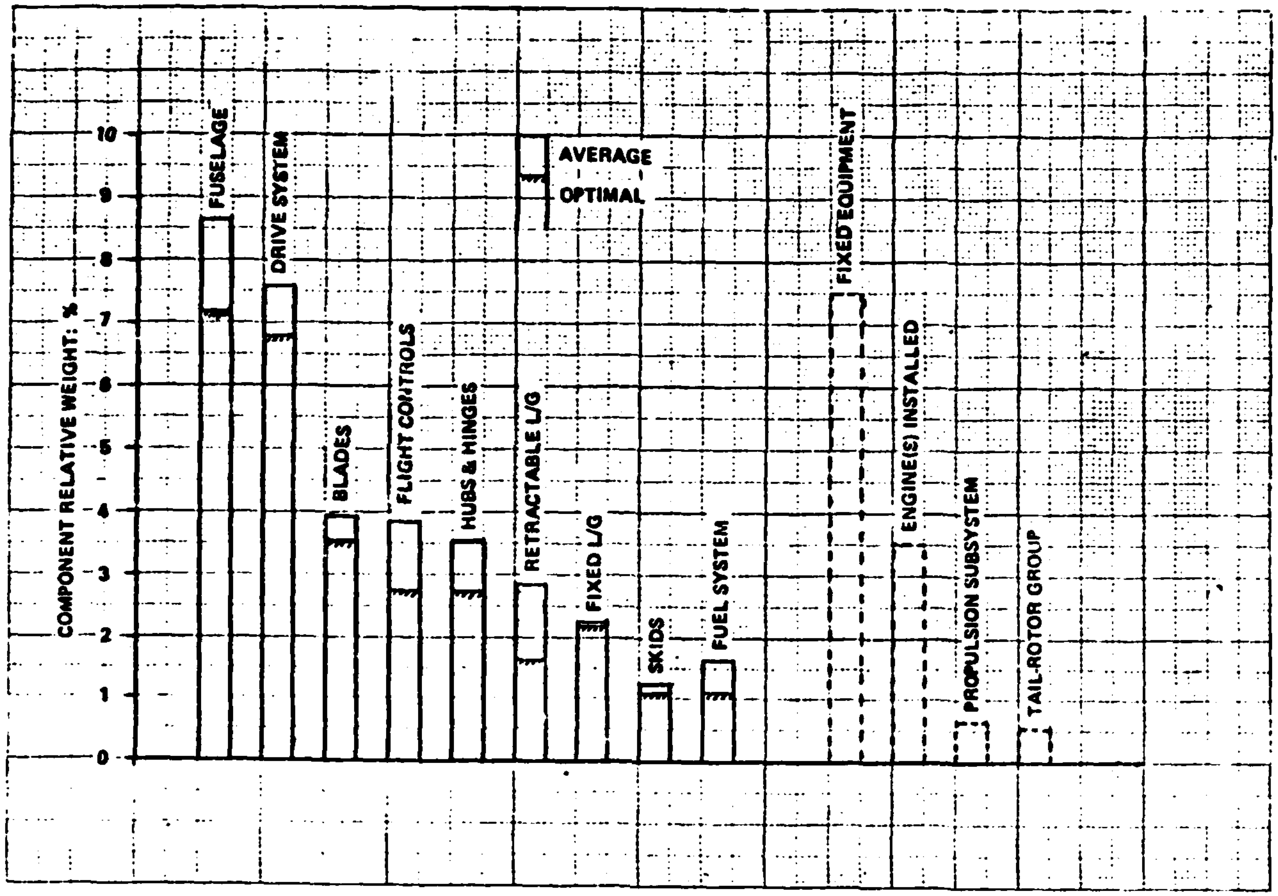


Figure 1.19 Average and optimal relative weights of major components for Western helicopters of the eighties

1.10.2 General Remarks

The usual way in which technology progresses is by minor improvements over a long time period, plus sudden introduction of major breakthroughs. The weight-reduction process as applied to rotorcraft is no exception to this rule, where the appearance of new high-strength materials may be regarded as the "breakthrough." In principle, this may produce a substantial reduction in weight. However, the weight reduction may be "used up" in meeting such requirements as increased life and crashworthiness. Also because of the lack of data on long-term field service life, conservative structural design is likely to be practiced, resulting in less weight reduction, but more confidence in the structural integrity of the component. As service life is accumulated, the weight may be reduced by redesign if the economics of the change are favorable to the customer by reducing costs and/or increasing payload or performance.

General comments regarding weight-reduction aspects of the major rotorcraft components discussed in this chapter will be given below in the same sequence as they appear in Figure 1.19. But there is one area which is difficult to assess; namely, the weight of vibration reduction devices which, in some configurations, may represent a significant contribution to the rotorcraft weight-empty.

1.10.3 Fuselage

All components which house the useful load, plus those that carry and transfer structural loads are included here. Thus, this category includes body, wing, tail, and some other items such as structural firewalls and equipment, and the support structure that may not normally be included in the above three groups.

It can be seen from Figure 1.19 that the fuselage as interpreted here represents the largest single relative weight item of all major helicopter components. Consequently, any significant reduction in the $\overline{W}_f$ level would have a considerable effect on lowering the helicopter weight-empty value. However, possible gains in that area are difficult to assess for different reasons, but there are two in particular. The first is comparative. How do you compare projected savings? Typically, this is done vs. an all-metal comparable vehicle, but the truth is that we can not do a good job of estimating an all-metal aircraft for the following reasons. First, there has been a gradual, but persistent, change in requirements, plus the gradual introduction of composites during the past several decades; notably, glass-fiber for secondary structure and, more recently, Kevlar and graphites. The second reason is that all-composite structures are still in the early stages of development. It remains to be seen how the materials and their protective coatings will hold up under extreme service and climatic conditions over the typical airframe lifetime. In the immediate future, it may be expected that unknown program risks may be avoided by adding extra plies of materials, etc., thus the weight savings may not reach estimates based exclusively on strength-weight considerations.

The use of new analytical methods should better enable assessment of composite weights; particularly since we are beginning to accumulate data from recent and current composite aircraft programs such as ACAP. In the future, we can expect design techniques that better integrate equipment, systems, and structures, including the impact of military requirements — all relying on CAD/CAM plus data bases.

The impact of detectability, crashworthiness, battle damage tolerance, etc., are difficult to assess, particularly when compared to an all-metal design, since the all-metal design should include all of the special features to the same standards as those of the composite structure. Nevertheless, judging from Figure 1.7, one may expect that the temporal trend of decreasing $\overline{W}_f$ values with time will continue in the future.

1.10.4 Drive System

The relative weight of the drive system, averaging about 7.5 percent for Western helicopters (Figure 1.19) and more for the tilt-rotor, represents the second largest contribution to relative weight-empty. Hence, here, as in the preceding case, reductions in $\bar{W}_{ds}$ values constitute a potential for lower $\bar{W}_e$ levels. Therefore, it is important to know the factors that have an influence on the relative drive-system weight. In this analysis, it may be convenient to focus one's attention on shafts and gearboxes. However, there is one item that is common to both; namely, bearings, as they considerably contribute to the drive-system weight. Unfortunately, weight increases rather than reductions, can be expected in the future along with the trend toward longer service life requirements. This is due to the fact that bearing size and weight are a function of their life to an exponent that is larger than unity. Only minor improvements in bearing technology can be expected to offset that trend within the next several years.

With respect to shafts, the use of drive shafting running at supercritical speed can substantially reduce the weight of long shafts; mainly, by eliminating some of the couplings and bearings that usually comprise the larger share of the shaft weight. Additional weight may be saved by using composite adapters. Thus, overall savings in shaft weights may be expected on the order of 20 to 40 percent when compared with metal shafting running at subcritical speeds[6].

Due to manufacturing constraints, the minimum composite tube wall for a shaft is about 0.080 to 0.10 inches thick. This minimum thickness impacts the weight as follows: obviously, for low-torque shafts, the tube will be over strength, since low torque is associated with small tube diameters, but with over-strength and stiffer tubes, the distance between bearings may be increased and, for a long shaft run, a bearing support and coupling set may possibly be removed. However, this is not as efficient as increasing the diameter-to-tube wall thickness (d/t) ratio where stiffness is desired.

Consideration of battle damage usually results in a tube diameter of about 4.5 inches. The combination of a 4.5-inch diameter tube plus a given wall thickness of 0.080 as a minimum will dictate the weight of the tubing run for small helicopters. The shaft rotational speed may affect the number of couplings required for long shaft runs.

For 4.5-inch aluminum tubes, the minimum wall thickness is approximately 0.060 inches; thus, it can be seen that the composite tube will be lighter than that of aluminum, since the density ratio favors the composite by almost 2 to 1.

It may be of interest to point out that for large helicopters, the tube diameter will usually exceed the 4.5-inch diameter. It can be shown that for long shafting runs, the weight is primarily determined by the distance between bearing supports (critical length). Critical length may be approximated by $C(P^{1/5}/N^{2/3})$, where P is power, N is rpm, and C is 8.4 for metals and 12.0 for graphite. In general, the roughly estimated weight of the proper composite shafts amounts to about 70% of that of aluminum and, in addition, the number of bearings and couplings may also be reduced (because of the longer critical length) to 70% of that for metal. Thus, the total weight of the long-run composite tube shafting may be approximately 0.7% of that of the metal type.

Trends in the weights of rotor shafts are difficult to assess due to the need of mating composites to metals at each end of the shaft, which would probably be required in currently envisioned applications. If the shaft is relatively short (as is usually the case), a weight increase will likely result, while the converse would be expected in a long shaft. If the typical planetary carrier is made of composite and integrated with the shaft, then a savings estimated to be on the order of 20 percent may be made on the combined carrier and shaft weight.

Focusing one's attention on gearboxes, it may be expected that they will have casings made of composites, with an attendant weight saving of 2 to 5 percent. Ref. 7 gives a good insight into this technological development.

Lubrication systems for gearboxes have not been investigated as seriously as other drive-system components. There are two heavy components in this system: blower and cooler. Other than the use of composites in the blower, little can be done to save weight since the cooler must basically transfer heat, and this is better done with metals, which brings up the following question. Will the loss of heat rejection of a composite vs. a metal gearbox case result in a cooler size increase, which would negate the weight saved by the composite case? For small boxes, this will probably be true.

The remaining components of the drive system are the rotor brake and clutches. Rotor-brake technology is similar to that for landing gears, since they both transfer large amounts of kinetic energy rapidly into heat. No significant weight savings are projected here. Clutches are of two main types: over-running, which are usually inside a gearbox and require no controls; and engaging clutches, which are usually remote control external devices. This type is seldom used, but when it is used, it can be quite heavy; thus, it is a candidate for weight-reduction, although there is no known specific program at this time.

1.10.5 Blades

Lifting blades represent the third major component (see Fig. 1.19) as far as its contribution to helicopter weight-empty is concerned. However, with $(\overline{W}_{bl})_{av} \approx 4$ percent, this contribution is much smaller than those of the fuselage and drive system. Furthermore, in rotor-blade design, the promise of weight reduction is not clear for the following reasons. First, autorotation capability and coning requirements may dictate blade mass (see Appendix A). autorotation capability and coning requirements may dictate blade mass (see Appendix to Ch. 2). Second, natural frequency is a significant driver of both structural weight (EI required) and weights required for mass distribution. In addition, blade strike, service life, battlle damage, thus negating weight saved by elegant design solutions using advanced materials.

However, the use of advanced materials (chiefly composites) may result in preventing weight increases, which should be considered of equal value to a weight decrease.

One area where weight can be, and sometimes is, reduced is at the blade root where the blade is attached to the hub. Since the attachment is usually so far inboard, it does not have a significant impact on autorotation capability. Ideally, new blade designs will have root ends, which consist of spar fibers continuing around a small sleeve; thus eliminating a separate and heavy root attachment fitting. Perhaps the flexure part of a simple hub can be integrated into the root end.

In spite of all the constraints regarding possibilities of making rotorcraft blades relatively lighter, Figure 1.3 suggests that some progress toward loweringthe $\overline{W}_{bl}$ values have been made through the years.

1.10.6 Flight Controls

The relative contribution of the weight of the flight-control system to the helicopter weight-empty is, on the average, similar to that of the lifting blades (about 3.8 percent as shown in Figure 1.19). As far as conventional controls (mechanical linkages, hydraulic boosters, and classical swashplates) are concerned, continuation of the present trend indicated in Fig. 1.17 may be expected. Which means that, looking at the overall distribution of points, only a slight reduction in $\overline{W}_{fc}$ values can be expected, although the optimal boundaries in Figures 1.17 and 1.19 suggest more spectacular possibilities.

However, the advent of "fly-by-wire" (FBW) and "fly-by-optics" (FBO) flight control systems plus the use of digital microprocessors, as well as the inclusion of automatic flight stability and flight-path control in future systems has resulted in a potential for weight reductions. There is also the possibility that further weight reductions may be achieved through the use of composites for cockpit controls, control actuators, rods, and cranks. In view of the rapid changes occurring in this area, it is difficult at this time to compare the overall impact of these new types of controls with the hydromechanical system, which will probably not be used on future military aircraft. When actual production hardware of the FBW and FBO type is developed and tested, a meaningful assessment of weight changes can be made.

1.10.7 Hubs and Hinges

The relative weight contributions of hubs and hinges to $\overline{W}_e$ at $(\overline{W}_h)_{av} \approx 3.5\%$ are quite similar to those of the lifting blades and flight controls. Consequently, reduction in the relative weights of hubs and hinges are equally important.

Beginning in the 1970's, the temporal trend of the relative hub weights given in Figure 1.5 shows a noticeable improvement in $\overline{W}_h$ levels. The introduction of titanium hubs resulted in a substantial weight reduction for a specific design application. This is clearly shown by the 1968 and 1972 points, where the upper points correspond to steel, while the lower ones correspond to titanium hubs for the same helicopters. Unfortunately, primarily because of the large variations in hub configurations and design requirements, the weight-reduction effect of titanium hubs is largely lost in the scatter of the trend.

The introduction of advanced composite materials has resulted in some dramatic weight reductions, even for the same helicopters (note the points corresponding to the 10,000 and 73,500-lb gross weights in Figure 1.6). But these gains are particularly remarkable where new simplified hub concepts have been applied. The structural properties of the advanced composite materials have, in large measure, contributed to these new concepts. Aerospatiale hub designs show spectacular achievements in weight reduction (see Figure 6 of Ref. 8). It remains to be seen if this improvement can be applied throughout all size ranges of helicopters.

With respect to Soviet hypothetical helicopters (Figure 1.6), it is of interest to note the range of hub-to-gross-weight ratios. The points for a 52 metric-ton helicopter of single-rotor, tandem, and side-by-side configurations are puzzling as to why such a large variation exists between the side-by-side and the tandem, which are both similar in concept except for orientation of the twin rotors.

It was expected that the teeter-rotor hubs would be lighter than articulated rotor hubs, but this is not true in general, although the more recent hubs are at the bottom edge of the total population.

The main conclusions to be drawn at this time are that there is a gradual decline in the hub weight-to-gross-weight ratio with time, and that simplified hub concepts plus the use of advanced composite materials will result in a significant reduction of the weight ratio especially in small helicopters and likely, in medium-size helicopters also. Further work may be required to determine the feasibility of applying these same concepts and materials to larger helicopters, and investigating whether similar weight-ratio reductions as those of the small helicopters can be obtained.

Materials other than advanced composites may also be developed that will enable the hub ratio trend in general to proceed along or near the $\overline{W}_h \approx 0.02$ values in the future. Looking at Figure 1.6, it should be noted that $\overline{W}_h$ values for the tilt-rotor are at the optimal boundary.

1.10.8 Landing Gears

One can see from Figure 1.19 that the relative weight of the landing gears may range from about 3% for the retractable type to as low as $\overline{W}_{lg} \approx 1.0\%$ for skids. For fixed type landing gears, the relative weights for contemporary helicopters is equal to about 2%. For crane-type helicopters, $\overline{W}_{lg}$ values as high as 4.3 to 6.8% may be expected (Figure 1.9). Consequently, the potential contribution of lower $\overline{W}_{lg}$ levels to relative weight-empty would be governed by the type of landing gear.

As far as possibilities of reducing relative landing-gear weights in general are concerned, advanced high-strength materials should contribute to that process, since a considerable portion of the landing-gear weight consists of load-carrying elements which can be made lighter using materials with better weight-strength characteristics.

The trend curves depicted in Figures 1.9 and 1.10, and the bar graphs shown in Figure 1.19 seem to clearly indicate a possibility for the use of relatively light retractable landing gears for helicopters, where a large difference between average and optimal $\overline{W}_{lg}$ values have already been demonstrated.

Although there are no similar major differences between optimal and average $\overline{W}_{lg}$ levels for fixed landing gears, the temporal trend of Figure 1.9 indicates a steady decline in $\overline{W}_{lg}$ values with time. However, no such trend seems to exist as far as skids are concerned — here, the $\overline{W}_{lg}$ level appears constant through the years.

1.10.9 Fuel System

It can be seen from Figure 1.19 that the average relativ[illegible] system weight for Western helicopters of the eighties amounts to about 1.6%, while the optimal level is about 1 %. However, as can be noted from Figures 1.15 and 1.16, large deviations up from the average values are encountered, especially for military helicopters, where the crashworthiness and self-sealing requirements are incorporated (see Section 1.8). It is obvious that under these conditions, the $\overline{W}_{fs}$ contribution to the relative weight-empty of a rotorcraft may not be negligible.

In view of the uncertainties regarding safety requirements, it is somewhat difficult to ascertain the influence of new materials (not only structural, but also sealers) on the relative weight of the fuel system. Nevertheless, it may be stated in general that although the $\overline{W}_{fs}$ values of future rotorcraft may rise, these increases would not be as high as they would have been without proper application of these new materials (both structural and nonstructural).

1.10.10 Major Rotorcraft Components Not Investigated in this Chapter

A glance at Figure 1.19 indicates that of the four major components not investigated in this chapter, the fixed equipment consisting of the following represents the highest relative weight value:

instrument and navigation group
hydraulics and pneumatic group
electrical group
electronics group
armaments (including gunfire protection)
furnishings and equipment group
airconditioning and anti-icing equipment
loading and handling equipment
avionics.

It is obvious that any appreciable change in the $\bar{W}_{fe} \approx 7.5\%$ level would exert an important influence on the rotorcraft relative weight-empty figure. Unfortunately, except for stating a truism that it is desirable to make the $\bar{W}_{fe}$ as low as possible, little else can be said regarding the possible influence of advanced technology materials on reductions in $\bar{W}_{fe}$ values. Furthermore, it should be remembered that the amount of fixed equipment on a rotorcraft is, to a large extent, dictated by the customer. In many cases, this involves selection of "off-the-shelf" hardware that has been qualified to MIL Standards and thus, there is a reluctance to change it, due to cost impact. However, some of the items could be reduced in weight by simple redesign of cases, racks, and plugs. This is particularly true of the avionics group, plus some electrical items.

Recently, there has been more emphasis placed on the reduction of vendor-supplied item weights. It is expected that this emphasis, plus some timely contracts, will result in substantial reductions in the weights of some fixed equipment. For example, why not integrate the equipment case with supports? In some instances, this may be achieved with good results.

With respect to the relative weight trends of the other three major aircraft components not discussed in any detail in this chapter, engines deserve a separate study which would go beyond the $\bar{W}_{en}$ aspects to include such topics as specific fuel consumption and others.

In spite of the fact that the propulsion subsystem at $\bar{W}_{pss} \approx 0.75\%$ represents next to the lowest relative weight of major components (Figure 1.10), it should not be excluded from an effort to further reduce the $\bar{W}_{pss}$ level. In this respect, one could find that new materials (both structural and nonstructural) might contribute to a relatively lighter propulsion subsystem.

As to the last item in Figure 1.10, namely, the tail-rotor group, one may state that here, also, potential advantages offered by advanced technology materials toward reduction in $\bar{W}_{tr}$ values should not be overlooked. This, in spite of the fact that small variations from the average level of $\bar{W}_{tr} \approx 0.6\%$ would have little influence on the overall relative weight-empty values.

1.11 Concluding Remarks

One of the most important factors in making any aircraft and rotary-wing configurations in particular, an operational success, is keeping the weight-empty to gross-weight ratio as low as possible. This ratio (called relative weight empty $\overline{W}_e$) is, in turn, a sum of the relative weights of all the major rotorcraft components. Thus, for a better understanding of the possibilities for achieving low $\overline{W}_e$ values, it is important to determine the temporal trends and effects of rotorcraft size (measured here through W_{max}) with respect to the relative weights of the components. This approach should provide an important part of the foundation for investigating the influence of the applicaiton of new advanced materials to those components, and forecasting their impact on the $\overline{W}_e$ level of future rotorcraft.

Temporal trends and gross-weight class effects on relative weights are graphically presented and discussed for the following major components of Western and Soviet helicopters: (1) main-rotor blades, (2) hubs and hinges, (3) fuselages, (4) landing gears, (5) drive system, (6) fuel system, and (7) flight-control group. For various reasons explained in the text, the remaining four major components; namely, (a) fixed equipment, (b) engines, (c) propulsion subsystems, and (d) tail-rotor group, are only briefly discussed here.

Unfortunately, with respect to the components discussed in detail in this chapter, some interesting data, for instance, that related to helicopter components made of new advanced composite materials, as well as nonhelicopter rotorcraft components, could not be included in this study because of proprietary aspects.

Also, figures regarding component weights of contemporary Soviet helicopters were not available to this investigator. However, to compensate for this drawback, all trend figures in this chapter are reproduced on a sufficiently large scale as to enable the reader who has access to the missing data, or wants to initiate his or her own projection of a component weight could plot points representing that additional information. In this way, as well as by adding points representing data which may become available to the public domain in the future, this chapter could become a "living document."

It is believed that the current trend graphs, based on a 'wide-as-practical' statistical basis, could be of real help in the following areas: (a) development of realistic requirements and specifications for new rotorcraft, (2) judgement of the 'goodness' of a major component from the point of view of weight in new designs, and (c) selection of the most 'profitable areas' as far as reduction of rotorcraft relative weight empty is concerned, and then channeling research and development efforts in that direction.

CHAPTER 2

INFLUENCE OF MATERIAL CHARACTERISTICS ON WEIGHTS OF STRUCTURAL ELEMENTS

2.1 Introduction

In order to evaluate the impact of advanced structural materials on weights of major helicopter components, the relationships between the weight of simple structural elements, various loading modes, and principal characteristics of various materials must be reviewed first. Once this task is accomplished, one can proceed toward forecasting variations in the relative weights of the major rotorcraft components by singling out the type of loading (tension, compression, torsion, elastic deformation, etc.), acting on the most important structural elements of the considered component. In this analysis, one should remember that structural elements of all rotorcraft are usually subjected to repeating loads of various frequencies throughout the operational life of the aircraft. Thus, the magnitude of the total number of cycles would be influenced, among others, by the following three major parameters: (1) intended operational life, (2) type and size of aircraft, and (3) mode (also known as profile) of typical operations. Consequently, all three aspects must be somehow reflected in the relationship between the principal material characteristics and the weight of the component.

With respect to the presentation of the influence of new materials on the component weight, it appears that one of the most suitable methods would be (because of the clarity in showing its relationship to the relative weight-empty of the rotorcraft) to establish the ratio of the relative weight of a major component fabricated from advanced materials to that of the corresponding component fabricated from traditional materials. In other words, the "traditional" component would serve as a baseline for measuring the actual or potential progress in structural weight reduction through the application of advanced materials.

The above-mentioned aspects are discussed in some detail in this chapter. In those cases where, because of time and budgetary limitations, the investigation can not be carried to the desired depth, their direction is, at least, outlined, which should help future students of this subject.

2.2 Weight Effectiveness Indices

Tension. *Assuming that an element of unit length ($l = 1$) made of material n is subjected to a tensile load of T lb (Figure 2.1), the weight of the element would obviously be*

$$W_n = 1 \times (T/s_t)\gamma_n \tag{2.1}$$

where s_t is the permissible stress in lb/in^2 (i.e., including all the applicable safety factors) corresponding to the assumed mode of loading (e.g., either static, or recurring so many times during the assumed life-span of the component), and γ_n is the specific weight (lb/in^3) of the structural material.

One can see from Eq. (2.1) that for T = const, the weight per unit length of the element will be proportional to the quantity

$$(\eta_n)'_t = \gamma_n/s_t. \tag{2.2}$$

In contrast, one may say that "lightness" of the element will be proportional to the reciprocal of Eq. (2.2), i.e.,

$$(\eta_n)^*_t = s_t/\gamma_n \tag{2.2a}$$

which can thus be called *the material weight-effectiveness index* in tension.

Further examining Eq. (2.2a), one would note that the ratio on the right side of the equation has the dimension of length, which can be interpreted as a length in inches of a ribbon or road having a constant cross-section which, when hung vertically from some kind of support, will produce the permissible tensile stress in the uppermost section of that ribbon or road. For instance, for steel ($\gamma_{st} \approx 0.282$ lb/in^3) having an ultimate tensile strength of $s_t = 190{,}000$ lb.in^2, the weight-effectivensss index would amount to $(\eta_{st})^*_t \approx 673{,}760$ in. Such a length expressed in inches is rather difficult to visualize. Thus, in order to provide the reader with a quantity more easily comprehended, it is proposed that the weight-effectiveness index for the case of tension be redefined, and expressed in feet instead of inches.

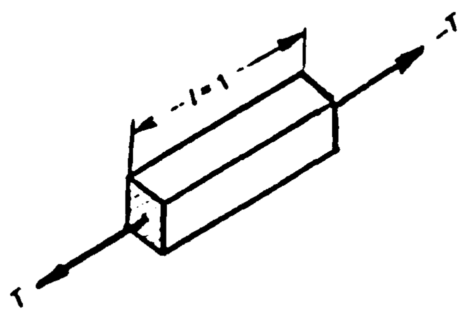


Figure 2.1 Scheme of loading in pure tension

Consequently, Eq. (2.2a) is rewritten as

$$(\eta_n)_t = s_t/(12\gamma_n). \tag{2.3}$$

Then, for the previously considered case of the ultimate strength of steel, the weight effectiveness index would be $(\eta_n)_t \approx 56{,}146$ ft.

Compression. The same reasoning as in the preceding case can be applied to compression, and the weight-effectiveness index can be expressed (in feet) as follows:

$$(\eta_n)_c = s_c/(12\gamma_n). \tag{2.4}$$

where s_c is the compression stress allowable for the considered mode of loading. The numerical value of $(\eta_n)_c$ can be imagined now as a height (ft) of a vertical column of a uniform cross-section made of the considered material which, under its own weight, would produce the allowable compressive stress at the cross-section at the base of the column.

Bending. In order to develop weight-effectiveness indices in bending, two very simple models of beams are considered. In the first case, it is assumed that the beam consists of a relatively thin walled cylinder, where thickness $t \ll d$ is uniform for the whole cylinder having a mean diameter of d (Fig. 2.2(a)).

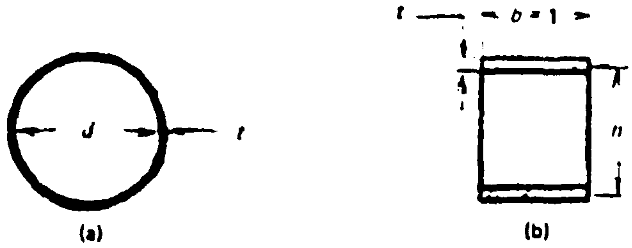


Figure 2.2 Schemes of beam cross-sections

In the second case, the beam cross-section is assumed to consist of two (again, relatively thin) flanges ($t_t \ll h$ and $t_c \ll h$), made of material for which a weight-effectiveness index has to be established, and is connected by two "weightless" webs.

Weight per unit length of the cylinder can be expressed as

$$\widetilde{W}_{n_{cyl}} = \pi d t \gamma_n, \tag{2.5}$$

where thickness t can be found as follows: Under the $t \ll d$ condition, the section modulus for the cross-section can be expressed as

$$I/(\tfrac{1}{2}d) = \pi d^2 t/4 \tag{2.6}$$

and thus for the bending moment M_b, the corresponding stress s_b would amount to

$$s_b = 4M_b/\pi d^2 t$$

and

$$t = 4M_b/\pi d^2 s_b. \tag{2.7}$$

Substituting Eq. (2.7) into Eq. (2.5), one obtains

$$\widetilde{W}_{n_{cyl}} = (4M_b/d)(\gamma_n/s_b). \tag{2.8}$$

It can be seen from Eq. (2.8) that assuming M_b = const and d = const, the weight of the structure would be proportional to the (γ_n/s_b) ratio and thus, its "lightness" would depend on the inverse of that ratio. Hence, as in the cases of tension and compression, as well as in bending of relatively thin-walled beams having a circular section, the (s_b/γ_n) ratio can also be considered as an index of lightness.

In the case of a two-flange beam, let it be assumed that either flange can work in tension or compression. Consequently, the thickness (t) of the lower and upper flanges will be assumed to be the same (see Fig. 2.2b). The weight per unit-length of such a unit-wide beam now becomes

$$\widetilde{W}_{n_{2fl}} = 2t\gamma_n. \tag{2.9}$$

Assuming that moment M can generate either a tensile force (T) or a compression force (C) acting on the flanges, the absolute magnitude of these forces can be expressed as

$$|T| = |C| = M_b/h \tag{2.10}$$

and, in turn,

$$t = M_b/hs_b, \tag{2.11}$$

where s_b is the allowable stress in the assumed mode of bending. Substituting Eq. (2.11) into Eq. (2.9), one obtains

$$\widetilde{W}_{n2fl} = 2(M_b/h)(\gamma_n/s_b) \tag{2.12}$$

It can be seen from Eq. (2.12) that, similar to Eq. (2.8) when both M and h are constant, the weight of the two-flange beam is proportional to the (γ_n/s_b) ratio. Thus, the weight-effectiveness index of material in bending can be defined in the case of tension and compression as

$$(\eta_n)_b = s_b/(12\gamma_n). \tag{2.13}$$

Elastic Buckling. The influence of material properties on the weight of structural elements designed for elastic buckling is examined by considering this mode of deformation for a strut of length l with a circular cross-section and a relatively small wall thickness in comparison with the diameter ($t \ll d$). The rod is permitted to buckle at a compressive force P_e. Fig. 2.2a, previously used for bending considerations, can also be applied to the present case. As a result of this assumption, the weight per unit length can be expressed (as in the case of bending) by Eq. (2.5). However, the wall thickness will now be governed by Euler's formula for a buckling load.

$$P_e = \pi^2 EI/l^2 \tag{2.14}$$

where P_e is the Euler buckling load, E is the modulus of elasticity, I is the sectional moment of inertia about the diameter, and l is the length of the strut.

For the assumed cross-section characteristics, I can be written as

$$I = (\pi/8)td^3. \tag{2.15}$$

Substituting Eq. (2.15) into Eq. (2.14) and solving for t, we have

$$t = (8/\pi^3)P_e l^2/d^3 E. \tag{2.16}$$

Substituting, in turn, Eq. (2.16) into Eq. (2.5), we obtain the weight per unit length in the case of buckling

$$\widetilde{W}_{bu} = (8/\pi^2)P_e l^2 \gamma/d^2 E. \tag{2.17}$$

One can see that assuming that P_e = const, l = const, and d = const, the unit weight of the strut is proportional to the (γ/E) ratio. Thus, as in the prevous cases, it may be stated that its "lightness" is governed by the (E/γ) ratio. Again, as before, the dimension of this ratio is length which again, can be expressed in feet; thus, the weight-effectiveness in strut buckling can be defined as

$$\eta_{bu} = E/12\gamma, \tag{2.18}$$

where the modulus of elasticity E is given in psi, and the specific weight of the material (γ) is in lb/in^3.

Torsion. The indices of the material weight effectiveness for structures loaded in torsion will be established by considering the following: (a) structural strength, and (b) elastic deformation. To keep the problem as simple as possible in both cases, a cylindrical structure having a circular cross-section and relatively thin walls in comparison with the structure diameter ($t \ll d$) will be examined (Fig. 2. 3).

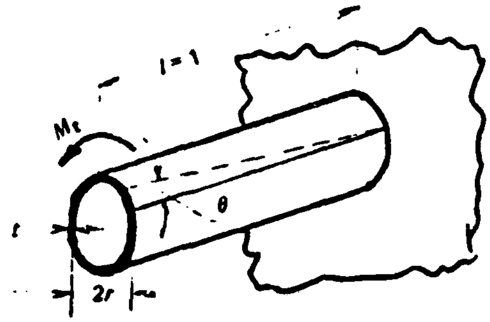


Figure 2.3. Scheme of structures loaded in torsion

As in the previously considered cases, the weight of the structure per unit length will be expressed by Eq. (2. 5). However, in the present case, the wall thickness will be determined from the following expression for shear stress.

$$s_{sh} = M_t/2\pi r^2 t$$

and thus,

$$t = M_t/2\pi r^2 s_{sh}, \qquad (2.19)$$

where M_t is the twisting moment of the structure, and s_{sh} is the allowable shear stress of the material.

Substituting Eq. (2.19) into Eq. (2.5), the following expression for the structural weight per unit length is obtained

$$\widetilde{W}_{to_s} = (M_t/r)(\gamma/s_{sh}). \qquad (2.20)$$

It can be seen from this equation that for M_t = const and r = const, the unit weight of the structure will be proportional to the (γ/s_{sh}) ratio. Thus, similar to the previous cases, its "lightness" can be judged by the following weight effectiveness index in torsion when the strength of the structure is a governing factor:

$$\eta_{to_s} = s_{sh}/12\gamma \qquad (2.21)$$

Here, again with s_{sh} in psi and γ in lb/in^3, η_{to} would be in inches; hence, in order to express this quantity in feet, a factor of 12 is introduced into the denominator of Eq. (2.21).

When the magnitude of the elastic torsional deformation represents a design criterion, the required wall thickness can be determined from the following expression, which gives the twist angle of the structure (see Fig. 2.3) per unit length ($\widetilde{\theta}$):

$$\widetilde{\theta} = M_t/2\pi r^3 tG, \qquad (2.22)$$

where G is the modulus of rigidity (psi).

Solving Eq. (2.22) for t, and substituting that value into Eq. (2.5), the following expression for the structural weight per unit length for the case of elastic deformation is obtained:

$$\tilde{W}_{to_e} = (M_t/r^2\theta)(\gamma/G). \tag{2.23}$$

In analogy to the previously considered cases, the material weight effectiveness index (feet) for torsional deformation can be defined as

$$\eta_{to_e} = G/12\gamma. \tag{2.24}$$

Panels in Tension or Compression. *For such semi-monocoque and monocoque structures as, for instance, fuselages, the component weight is usually related to the wetted area. Consequently it becomes important to know how material characteristics affect weight per unit of area (say, one sq.ft) of the structure. One can imagine these unit areas as panels loaded in tension, compression, or shear. However, it appears that in actual helicopter design practice, tensile and compressive loads, rather than shear, dictate the dimensions of the panel section and thus, their unit weight. For this reason, material weight-effectiveness indices will be established for panels in tension and compression only.*

Denoting the weight of the panel per sq.ft by $\tilde{w}$, and assuming that under operational conditions reflecting, among other factors, the number of loading cycles during the anticipated life flight of the component, the panel can sustain, say, a tensile load, τ_t, expressed in pounds per running foot of the panel cross-section (see Fig. 2.4). Under these assumptions, the material weight-effectiveness in tension of a panel of unit area index in tension can be readily deduced as

$$\eta_{pe_t} = \tau_t/\tilde{w}_t. \tag{2.25}$$

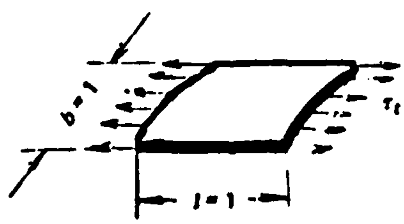


Figure 2. 4 Loading scheme in tension of a panel of unit area

For the case of compression, Eq. (2.25) becomes

$$\eta_{pe_c} = \tau_c/\tilde{w}_t, \tag{2.26}$$

where τ_c is the allowable load per running foot in compression.

Looking at Eqs. (2.25) and (2.26), one can see that they have a dimension of length in feet. Similar to Eqs. (2.3) and (2.4), those indices can be interpreted as the length of an imaginary vertically suspended ribbon in the case of tension, and an imaginary vertical column in the case of compression, which would produce (at the uppermost in the first, and lowest in the second case) the allowable loads per running foot.

2.3 An Alternate Definition of Weight-Effectiveness Indices

It was shown in the preceding section that the appropriate allowable stress to the material specific weight ratio represents a meaningful weight-effectiveness index for simple structural elements being stressed in tension, compression, bending, and shear. For cases involving linear and torsional rigidity, the E/γ and G/γ ratios, respectively, represent the weight-effectiveness indices.

It should be indicated at this point that although expressing the weight-effectiveness indices of materials in feet rather than in inches may enable one to better visualize the lengths indicated in these indices, inches are usually quoted in U.S. literature. In the metric system, the weight-effectiveness indices for materials are given in more easily imagined meters.

An alternate way of expressing the weight effectiveness of materials may be based on the specific gravity of the material. In this respect, one should note that the specific weight (γ) appearing in the denominators of all indices can be written as

$$\gamma_n = \gamma_{we}\delta_n \tag{2.27}$$

where γ_{we} is the specific weight of distilled water at 4°C, and δ_n is the specific gravity of the considered structural material.

Since, obviously, γ_{we} = const, it may be considered that all of the weight-effectiveness indices developed in Section 2.2 for any material and mode of loading are proportional to the quantity represented by the ratio of allowable stress to the specific gravity of the material:

$$\eta_n \sim s_n/\delta_n. \tag{2.28}$$

For the elastic deformations of the linear type,

$$\eta_n \sim E/\delta_n \tag{2.29}$$

and for those in torsion,

$$\eta_n \sim G/\delta_n. \tag{2.30}$$

One can see, hence, that the ratio expressed by the right sides of Eqs. (2.28) through (2.30) may be considered as alternate definitions of the weight-effective indices; this time, expressed in units of force per unit of area.

The above-described method of presenting weight-effectiveness indices of structural materials is also quite popular in technical literature.

2.4 Effects of Repeated Loadings on Weight-Effectiveness Indices

2.4.1 General

In the weight effectiveness indices developed in the preceding section stress allowable (s), as well as moduli of elasticity (E) and rigidity (G), always appeared in the numerator of the formulas, thus indicating that "goodness" of a structural material from the point of view of lightness of a structure is proportional to those characteristics. It is obvious, hence, that factors affecting the permissible levels of s, E, and G of a given structural material should be investigated.

2.4.2 Fatigue Effects on E and G Levels

With respect to the moduli of elasticity and rigidity, it appears that as far as metals are concerned within the whole possible operational envelope and time of rotorcraft operation, there would be no causes that would noticeably alter their E or G levels.

However, the situation is somewhat different with respect to composite structures, especially those consisting of laminates with various orientations of fibers. Structures of this type, when subjected to repetitive loadings, may undergo progressively increasing delamination which, in turn, would affect the E level of the structure. This aspect is discussed in more detail in Ref. 9, from which Figures 2.5 and 2.6 are reproduced and shown below.

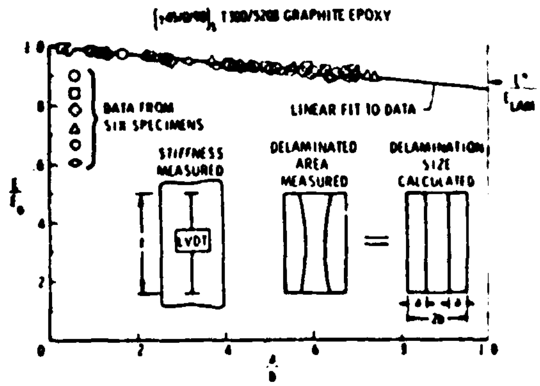


Figure 2.5 Modulus loss as a function of delamination size in $[\pm 45/0/90]_s$ laminates

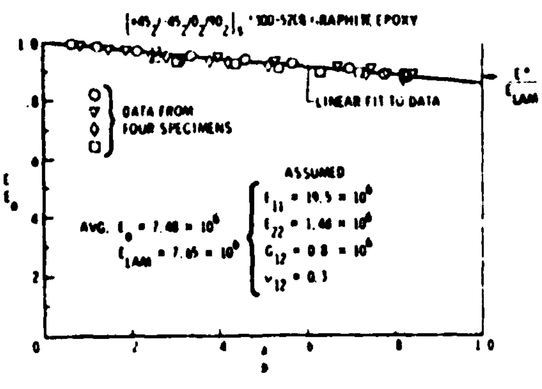


Figure 2.6 Modulus loss as a function of delamination size in $[+45_2/-45_2/0_2/90_2]_s$ laminates

Looking at these figures, one will see that even when the delamination is complete $(a/b) = 1.0$, the modulus of elasticity (E) of the structure would still amount to over 80% of the original value (E_0). Similar degradations can be expected with respect to rigidity (G) levels under repeated loading.

Although these changes in E and G levels of composite structures do not appear to be excessively high under repeated loadings, they may have significant effects on vibration and other characteristics of a rotorcraft. Thus, in principle, they should not be excluded from a study of the weight-effectiveness indices under fatigue conditions encountered by rotorcraft components during the operational life of the aircraft.

2.4.3 Fatigue Effects on Allowable Stresses

In contrast to practically no changes in E and G for metals, and relatively small ones for composite structures under repeated loading, the breaking and hence, allowable stress on metals as well as composites (be it tension, compression, bending, or shear), would vary considerably with the total number of loading cycles (N), as well as in light of other factors as indicated below.

The relationship between the breaking stress of a material and the number of repeated loading cycles experienced up to that point is presented under the form of the so-called S–N curve. Where the number of loading cycles is marked on the abscissa axis (logarithmic scale), while breaking stresses (in ksi) are shown on the ordinate axis (linear scale).

The general form of the S–N curve for any type of loading is sketched in Figure 2.7. It should be noted at this point that the data presented in this way usually covers the range of the number of cycles from 10^3 to 10^6 or 10^7. Also, the stress ratio ($R = s_{min}/s_{max}$) under which the S–N curve was established, and the ultimate strength of the material in the considered type of loading are usually given.

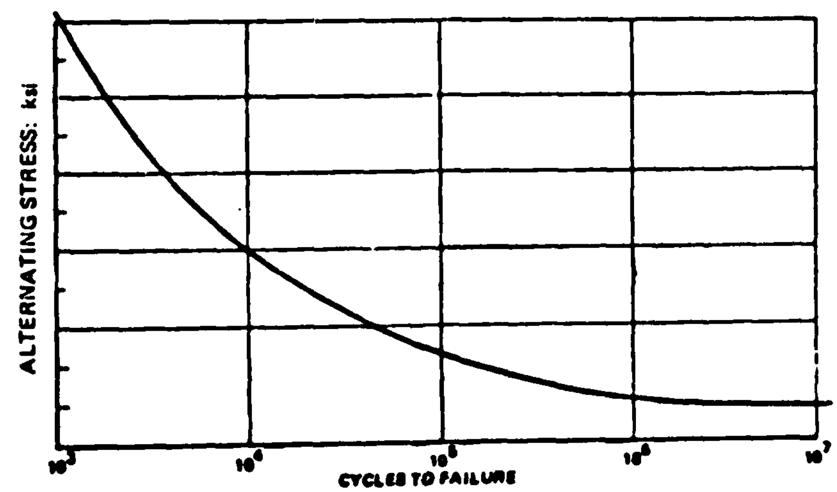


Figure 2.7 General form of the S–N curve

Although the number of loading cycles is the dominant factor in establishing the breaking stress levels, there are other factors also involved. The most important are:

a. loading configuration
b. stress concentrations
c. surface condition
d. environmental conditions
e. material processing parameters

Partially because of the above reasons and partially because of the additional uncertainty regarding the number of cycles that may be encountered at a particular stress level during the operational life of a component, rotorcraft designers tend to accept much lower allowable stress level values (s_{al}) than those actually given by the S–N curve.

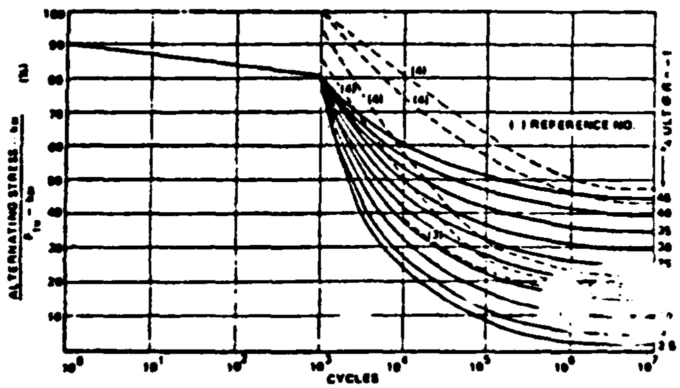


Figure 2.8 Nondimensionalized S–N curve for steel with a mean of zero percent of ultimate (Figure 6 from Reference 11)

It has already been mentioned that experimental data on the effects of repeated loading on the breaking stress are seldom available for the total number of loading cycles, especially at $N < 10^4$. However, there are some components (e.g., landing gears and transmissions), where maximal loadings occur only infrequently – for instance, during takeoffs and landings. Consequently, the total number of loading cycles acquired during the operational life of the rotorcraft may be below the N level for which experimental data is available. In view of this, methods were developed for establishing the shapes of the S–N curves for the total range of loading cycles ($1 \leqslant N \leqslant N_e$), where N_e is the number of cycles corresponding to the endurance limit (s_e), i.e., a point where a further increase in the number of loading cycles does not produce any decrease in the breaking stress.

In this respect, a method originally proposed in the sixties by Albrecht[10] and recently refined may be used for determinations of the S–N curve for the allowable stresses throughout the whole range of repeating cycles[11].

One approach presented in Ref. 11 permits one to generate nondimensional S–N curve shapes for steel and aluminum alloys using only available high-cycle fatigue data. These generalized curves, expressing the ratio of alternating breaking or somewhat lower allowable stresses in ksi to ultimate tensile allowable (F_{tu}) in ksi are plotted as a function of the number of cycles (Figure 2.8). This figure was established for steel experiencing a load ranging from $-s_{max}$ to s_{max}, i.e., at $R = -1$, but no steady load (a mean of zero percent). Within the $1 \leq N < 10^3$ interval, the $(s_{al}/F_{tu}) = f(N)$ relationship is represented by a straight line. However, from $N = 10^3$, a series of curves are shown whose shape depends on the ratio of the endurance limit (s_e) to the ultimate tensile allowable.

When representative loading cycles occur in the presence of a steady load, the shape of the S–N curve would change, depending on the magnitude of the steady stress to the ultimate. Figure 2.9 is given here as an example of those changes when the steady stress amounts to 25% of the ultimate.

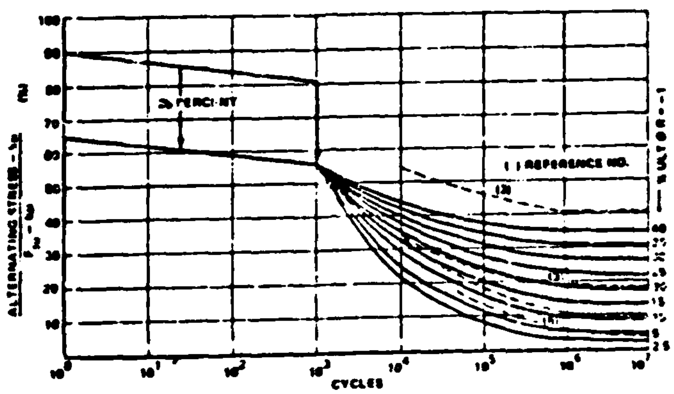


Figure 2.9 Nondimensionalized S–N curve for steel with a mean of 25 percent of ultimate

Obtaining a complete S–N curve in ksi vs. N for steel or aluminum alloys with the help of the nondimensionalized plots of Reference 11 can be done as follows.

Knowing the ultimate and endurance limit stresses for a given material, the type of loading, and anticipated surface conditions (smooth, notched), the allowable stress in ksi at any N value can be computed by simply multiplying s_{ult} in the notation of Ref. 11, or s_{ult} in our notations, by the proper ordinate value from the nondimensionalized curve.

Once the $s_{al} = f(N)$ is known, the weight effectiveness indices for various metallic materials and/or loading modes, etc., can be computed by using the relationships developed in Sections 2.2 and 2.3.

As an example, the $(s_{al}/\delta) = f(N)$ curves were determined for 4130 steel (140.0 ksi UTS, $s_e \approx 38.5$ ksi, i.e., ULT = 27.5%), and aluminum alloy 24S-T (65.0 ksi ULT, $s_e \approx 14.0$ ksi, i.e., ULT ≈ 21.5%), assuming that $R = -1$ and that the mean load is equal to zero (Figure 2.10). This was done using Figures 6 and 14 of Reference 11, and remembering that specific gravity is $\delta \approx 7.8$ for steel, and about 2.7 for aluminum alloy.

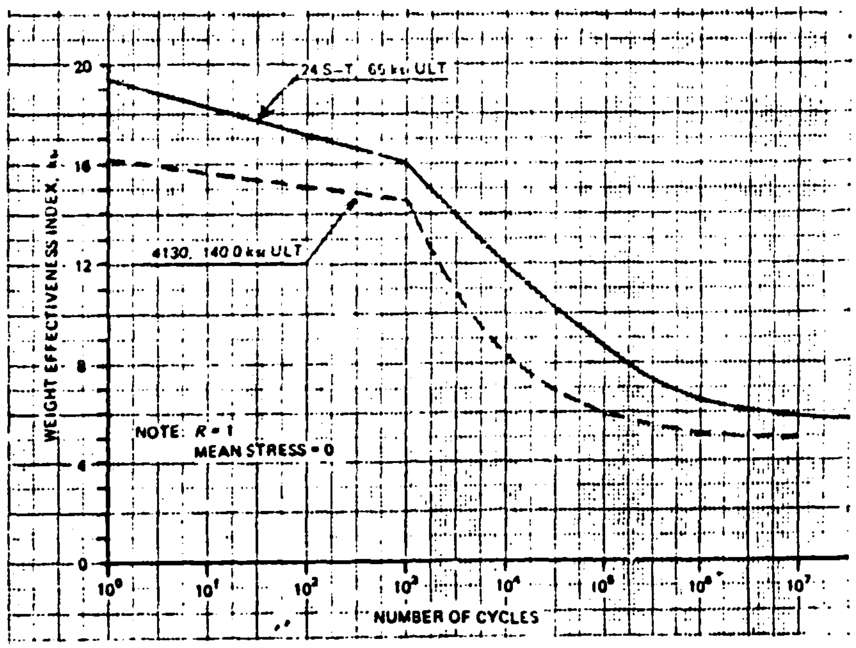


Figure 2.10 Example of weight effectiveness indices for aluminum alloy and steel under fatigue conditions

The above-outlined approach for predicting the total S–N curves, based on Ref. 11, can be extended to nonmetallic materials such as composites, while the basic information regarding the fatigue properties of structural materials (usually at $N > 10^4$) can be found in such publications as MIL Handbook–5D[12] with respect to metals. There is no similar handbook-type, single-source information for composites. Consequently, the necessary data must be assembled from such publications as company brochures (e.g., Dupont and Hercules) and professional journals.

2.5 Influence of Life-Span on the Weight of a Component

The rotorcraft manufacturer usually specifies two types of life for major helicopter components. One is chronological, given in calendar years of service, and another is the operational life based on total flying time through which the helicopter can safely operate. There are also specified times between overhauls (TBO).

The so-called calendar life reflects the fact that such structures as aircraft in general (including helicopters), when exposed to the operational environment may undergo deterioration with time, to some extent, independent of actual flying time. Although there may be some relationship between the weight of a component and its calendar life (for instance, heavier gauges of external metal surfaces, or special paints, may contribute to a longer calendar life), the latter still probably represents second-order effects on component weights. In contrast, the influence of the operational life and mode of operation (operational profile) are of prime importance, as they influence the total number of loading cycles and magnitude of loads experienced by a component during that period and thus, determine the allowable design-stress level. The lengths of TBOs probably also represent second-order effects on component weights since during those operations, the main structural load-carrying elements (unless visibly damaged) are not usually replaced.

Consequently, it appears that only the relationship between the operational life of the component and its weight should be investigated.

It has already been mentioned that during the operational life of a rotorcraft, its components experience two types of repeating loadings. One, depending on the anticipated number of operational events (e.g., takeoffs and landings and high-load flight maneuvers) expected to occur during the operational life of a rotorcraft, and the other, having its source chiefly in the rotation of the lifting rotors. The first type is considered to be infrequent in comparison with the second. However, absolute numbers of such events encountered during the life of the rotorcraft may be quite high. For instance, during one logging operation, some helicopters encountered as many as 720,000 trip cycles. Although in each of these events, there were no takeoffs and landings, the power excursions frequently varied from zero to rated power[14].

The whole area of estimating the total number of loading cycles acquired during the operational life of a rotorcraft by its various components in conjunction with the operational profile, becomes more and more important, as witnessed by the constantly increasing number of studies and publications (e.g., Refs. 11, 13, and 14) dealing with this subject.

With respect to loadings whose origin may be traced to the rotational motion of the lifting rotors, the total number of loading cycles acquired through "normal" operation during the flight life of a helicopter can be expressed as follows:

$$(n_{cy})_{fl} = 60(\text{rpm}) \times T_{fl}(\text{cpr}), \tag{2.31}$$

where rpm is the rotor revolutions per minute, T_{fl} is the total projected helicopter life span expressed in flight hours, and cpr is the number of loading cycles per revolution.

For contemporary helicopters, usually having a specified life span of at least 5000 hours, even the number of 1/rev cycles will be quite large. One can see from Figure 2.11, where $(n_{cy})_{fl}$ for 1/rev at 5000 hours are shown for the helicopters examined in Ref. 5, that even for the over 100,000-lb gross-weight class, the total number of 1/rev cycles would amount to about 4×10^{7}.

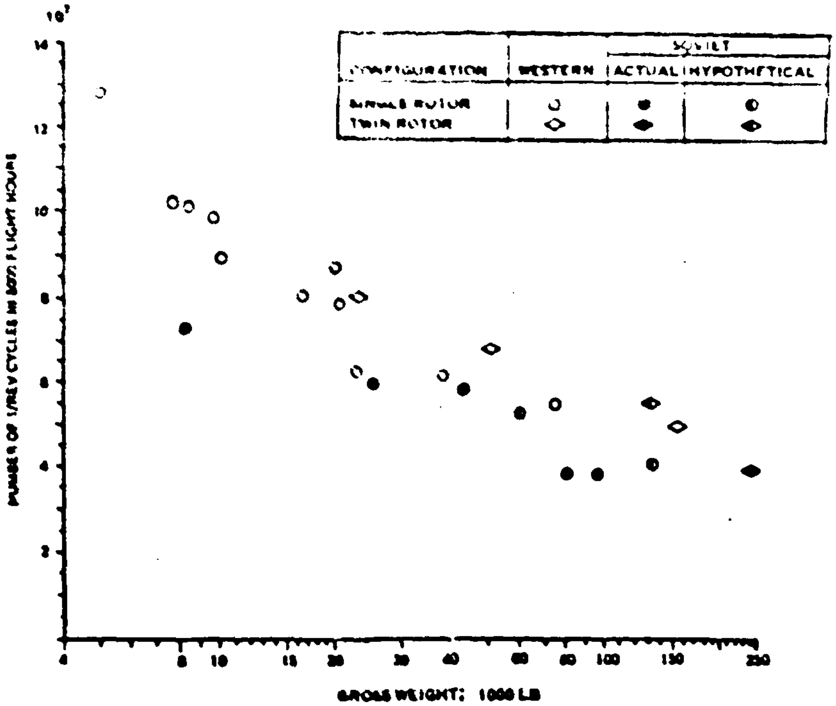


Figure 2.11 Total number of 1/rev cycles experienced by helicopters of various gross-weight classes during 5000 hours of normal operation

It may be anticipated, hence, that for rotorcraft components whose dimensions are dictated by repeated loads appearing at the 1/rev and higher cpr values, the endurance limits of structural materials would represent a decisive factor as far as the weights of the components are concerned.

2.5 Cursory Estimates of the Influence of Weight-Effectiveness Indices on Component Weights

2.5.1 General

One of the simplest ways for a priori judgement regarding the influence of advanced structural materials on the weight of a component would be by establishing a ratio between the weight of a component structured of new materials to the baseline weight of an existing component.

One may also use the weight estimated by reliable weight prediction methods for components made of "traditional" materials for which the correctness of the weight estimate method is well documented as a baseline reference (for example, see Ref. 1 for evaluation of various methods).

Once the absolute, or relative weight of the baseline component is known either by actual weight or through reliable calculations, the procedure for evaluating the impact of new materials on that weight will be the same

In the most general case the baseline and new components may be considered as being composed of no-load and load-carrying elements. The effect of material characteristics on the weight of no-load carrying elements will be examined first.

2.5.2 No Load Elements

Assuming that the baseline component weight is W_{n_0}, the weight of the no-load carrying elements (W_{nl_0}) can be expressed as

$$W_{nl_0} = \mu_{nl_0} W_{n_0} \tag{2.32}$$

where μ_{nl_0} is a fraction depicting the part of the total baseline component weight consisting of no-load carrying elements. Depending on whether W_{nl_0} represents the weight of a volume of material (e.g., fillers), or a surface (e.g., various no load carrying panels and fuselage surfaces), the weight of the no-load carrying elements can be expressed as

$$W_{nl_0} = V_{nl_0}\gamma_{n_0} = V_{nl_0}\gamma_{we}\delta_{n_0} \tag{2.33}$$

where V_{nl_0} is the volume of no-load carrying elements. The remaining symbols are defined in Section 2.2.

Or,

$$W_{nl_0} = S_{nl_0}\tilde{w}_{n_0} \tag{2.34}$$

where the new symbol S_{nl_0} is the no-load carrying surface in the considered element.

Assuming that either volume (V) or surface (S) of the component made of new materials is the same as that of the baseline component, the weights of no-load carrying components ($W_{nl_{nm}}$) in the case of volume becomes

$$W_{nl_{nm}} = V_{nl_0}\gamma_{we}\delta_{n_{nm}} \tag{2.35}$$

and that of the surface,

$$W_{nl_{nm}} = S_{nl_0}\tilde{w}_{n_{nm}} \tag{2.36}$$

Multiplying Eqs. (2.35) and (2.36) by $(\delta_{n_0}/\delta_{n_0})$ and (w_{n_0}/w_{n_0}) respectively, and noting that $V_{nl_0}\gamma_{we}\delta_{n_0} = W_{nl_0} = \mu_{nl_0}W_{n_0}$ and $S_{nl_0}w_{n_0} = W_{nl_0} = \mu_{nl}W_{n_0}$, these equations can be rewritten as

$$W_{nl_{nm}} = \mu_{nl_0}W_{n_0}(\delta_{n_{nm}}/\delta_{n_0}) \tag{2.37}$$

and

$$W_{nl_{nm}} = \mu_{nl_0}W_{n_0}(\tilde{w}_{n_{nm}}/\tilde{w}_{n_0}). \tag{2.38}$$

2.5.3 Load Carrying Elements

In the most general case, a major rotorcraft component may contain various elements whose dimensions and hence, their weight, are related to the loading mode in which they are working, namely tension, compression, bending, shear, elastic buckling, or linear deflection and torsional deflection. The fraction of the total component weight, which is taken by all of the above listed loading modes will be expressed through the following symbols: tension – μ_t; compression – μ_c; bending – μ_b; shear – μ_{sh}; buckling and linear deflection – μ_E, and torsional deformation – μ_G.

Consequently, the absolute weight of all the baseline component elements working under a particular loading mode, say for example in tension would be

$$W_{t_0} = \mu_{t_0} W_{n_0}. \tag{2.39}$$

Similar equations can be written for other groups of elements.

When new structural materials are substituted for those used in the baseline component, the influence of this substitution on the weight can easily be determined, using an approach similar to that outlined in the case of no-load elements. However, this time, ratios of weight effectiveness indices for the baseline and new materials would replace those of specific gravity [Eq.(2.37)], or weights per unit of area [Eq. (2.38)]. Thus, when made of new materials, the total weight of all the components working in tension will be.

$$W_{t_{nm}} = \mu_{t_0} W_{n_0}(\eta_{t_0}/\eta_{t_{nm}}). \tag{2.40}$$

2.5.4 Weight of a Component with New Materials in Relation to that of the Baseline

Taking into account both no-load carrying and load-carrying elements, the weight of a major rotorcraft component built from new materials ($W_{n_{nm}}$) can be expressed through the baseline component weight (W_{n_0}) as follows:

$$W_{n_{nm}} = W_{n_0}[\mu_{nl_0}(\delta_{n_{nm}}/\delta_{n_0}) + \mu'_{nl_0}(\tilde{w}_{n_{nm}}/\tilde{w}_{n_0}) + \mu_{t_0}(\eta_{t_0}/\eta_{t_{nm}}) +$$
$$\mu_{c_0}(\eta_{c_0}/\eta_{c_{nm}}) + \mu_{b_0}(\eta_{b_0}/\eta_{b_{nm}}) + \mu_{sh_0}(\eta_{sh_0}/\eta_{sh_{nm}}) + \mu_{E_0}(\eta_{E_0}/\eta_{E_{nm}}) +$$
$$\mu_{G_0}(\eta_{G_0}/\eta_{G_{nm}})]. \tag{2.41}$$

Obviously, the ratio ($W_{n_{nm}}/W_{n_0}$) of the new component weight to that of the baseline will be given by the expression contained in the brackets of Eq. (2.41).

2.5.5 Steps in Estimating the ($W_{n_{nm}}/W_{n_0}$) Ratio

The steps to be taken in the practical procedure of estimating the ratio of a major rotorcraft component weight to the weight of the baseline component can be visualized as follows.

1. Estimate the fraction of the total component weight representing the no-load carrying elements, and indicate whether these elements consist of filling some space, or form a surface.
2. Evaluate the weight fractions of elements working under various loading conditions, and determine the approximate number and character of loading cycles during the anticipated, or already established component operational life.
3. On the basis of the known number and type of loading cycles, estimate the weight effectiveness indices for the baseline and new materials from a graph similar to that shown in Figure 2.10.
4. Compute the new component weight to that of the baseline from the expression contained within the square brackets in Eq. (2.41).

2.6 Concluding Remarks

In order to obtain a better understanding of the relationship between principal characteristics of structural materials and weight of major rotorcraft components, the criteria for the weight-effectiveness of materials were first developed for simple cases of loading (tension, compression, bending, and shear), as well as buckling and linear deflection (influence of the modulus of elasticity, E) and torsional deflection (influence of the modulus of rigidity, G).

Following this, the influence of repeated loading cycles on values of the weight-effectiveness indices was examined. Then, the relationships between intended operational life of a component and operational profile of the rotorcraft on one hand, and the number of cycles that the component may experience on the other, was indicated.

Mathematical expressions for a cursory estimation of the weight ratio of a component made of new materials to that of the baseline component were developed in the preceding section. This was supplemented by an outline of the steps that should be taken when computing that weight ratio.

It should be noted at this point that the cursory expression given by Eq. (2.41) can be refined. This can be done by taking into account that the weight fractions (μ's) of elements working in a given loading mode in the new component may be different from those in the baseline. A study of the possible gains in accuracy resulting from this approach would be beneficial.

In order to facilitate the whole process of investigating the influence of new structural materials on the weight of major rotorcraft components, it would be desirable to develop a library consisting of weight-effectiveness indices for rotorcraft structural materials (similar to those shown in Figure 2.10), where values of the indices would be shown for the whole range of loading cycles from $N = 10^0$ to that corresponding to the endurance limit. Furthermore, this should be done for various stress ratio (R) values, surface conditions, and several steady load values (say, 12.5, 25, and 50% of the ultimate).

It should also be noted that in some cases, not all weight gains due to advanced materials as indicated by the procedures described in this chapter can be realized in practice. This is due to the existance of various constraints which may limit actual weight benefits to a lower level than indicated by Eq. (2.41). Requirements for maintaining a high axial moment of inertia for rotors, and coning angle for articulated blades may be cited as an example of such constraints.

More information regarding such constraints can be found in the Appendix to this chapter.

APPENDIX TO CHAPTER 2

POSSIBLE GAINS IN HELICOPTER BLADE WEIGHTS
THROUGH APPLICATION OF HIGH-STRENGTH MATERIALS

A.1 General

There is an established belief in some technical circles that weight-reduction attempts would be somewhat futile when directed toward helicopter rotor blades. This is supposedly due to the fact that requirements for a high moment of inertia about the rotor axis, facilitating transition into autorotation, and restrictions on the maximum permissible coning angle would constitute strong constraints inevitably leading to "heavy" blades. The following simplified calculations indicate that through the installation of concentrated tip weights as the structural weight of the blade itself is reduced, significant reductions of the overall blade weight are possible, while retaining moment of inertia and coning angle of the baseline helicopter. Reduction of blade weights and thus, their centrifugal force would, in turn, contribute to a possible decrease in the weight of the hub and hinges.

A.2 Moment of Inertia about the Rotor Axis

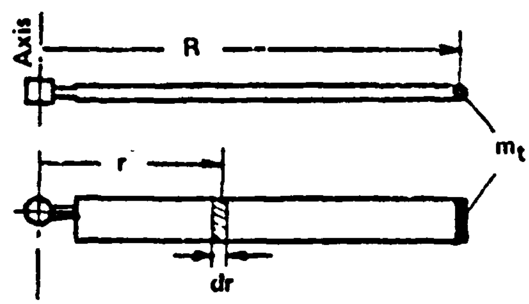


Figure A.1 Schematic of rotor blade

The total mass of the blade (m_{tot}) consists of the mass of the blade proper (m_{bl}) and mass of the tip weight (m_t).

$$m_{tot} = m_{bl} + m_t. \tag{A.1}$$

The blade moment of inertia about the rotor axis (I_{ax}) can be expressed as

$$I_{ax} = \int_0^R r^2 dm + R^2 m_t. \tag{A.2}$$

Assuming that the blade mass per running foot, $\tilde{m} = m_{bl}/R$ = const; and thus, $dm = \tilde{m}dr$, Eq. (A.2) can be rewritten as follows:

$$J_{ax} = \tilde{m}\int_0^R r^2\,dr + R^2 m_t \tag{A.2a}$$

or

$$J_{ax} = (1/3)\tilde{m}R^3 + m_t R^2. \tag{A.2b}$$

but $\tilde{m}R = m_{bl}$, hence

$$J_{ax} = R^2[(1/3)m_{bl} + m_t]. \tag{A.2c}$$

Assuming that the baseline blade has no tip weight ($m_{t_0} = 0$), its moment of inertia would be

$$J_{ax_0} = (1/3)m_{bl_0}R^2. \tag{A.3}$$

If the mass of the proper lighter blade is $m_{bl} = m_{bl_0}\alpha$, where $0 \leq \alpha \leq 1.0$, then the condition of the constancy of J_{ax} can be expressed as follows:

$$(1/3)m_{bl_0}R^2 = R^2[(1/3)m_{bl_0}\alpha + m_t]$$

from which

$$m_t = (1/3)m_{bl_0}(1-\alpha) \tag{A.4}$$

and the total mass of the lighter blade will be

$$m_{tot} = m_{bl_0}\alpha + (1/3)m_{bl_0}(1-\alpha). \tag{A.5}$$

The ratio of the total mass of the lighter blade to that of the baseline blade will be:

$$(m_{tot}/m_{bl_0}) = \alpha + [(1/3)(1-\alpha)] = (2/3)\alpha + (1/3). \tag{A.6}$$

Eq. (A.6) is plotted in Figure A.2, and one can see from this figure that significant overall blade-weight savings can be achieved if the weight of the blade can be reduced below that of the baseline weight, and the condition of retaining the same moment of inertia about the rotor axis is obtained through installation of tip weights.

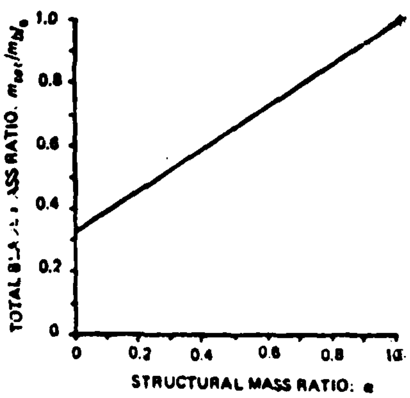


Figure A.2 Ratio of total blade mass to structural mass for J_{ax} = const

A.3 Blade Centrifugal Force Variation at J_{ex} = const

As the total blade mass and its distribution would vary when α changes in value, but J_{ex} remains constant, the blade centrifugal force can also vary. Ratio of the blade CF with tip weights to the CF of the baseline blade can be determined from the following.

The centrifugal force of the baseline blade (CF_0), with no tip weights, would be

$$CF_0 = \int_0^R \omega^2 r \tilde{m}_0 dr$$

or, assuming $\tilde{m}_0$ = const,

$$CF_0 = (1/2) m_{bl_0} R \omega^2. \tag{A.7}$$

The centrifugal force of a blade with tip weights will, in general, be

$$CF = \int_0^R \omega^2 r \alpha \tilde{m}_0 dr + \omega^2 R\, m_t.$$

Again, assuming $\alpha \tilde{m}_0$ = const, the above equation becomes

$$CF = (1/2) \alpha m_{bl_0} R \omega^2 + m_t R\, \omega^2. \tag{A.8}$$

Dividing Eq. (A.8) by Eq. (A.7), the sought ratio is obtained:

$$CF/CF_0 = \alpha + 2 m_t / m_{bl_0}. \tag{A.9}$$

But, in order to maintain J_{ex} = const as α varies, m_t must be as given by Eq. (A.4). Substituting Eq. (A.4) into Eq. (A.9),

$$CF/CF_0 = 2/3 + (1/3)\alpha. \tag{A.9a}$$

It can be seen from Figure A.3 that reductions in the blade centrifugal force – made potentially possible when the weight of the proper blade is reduced by a factor of α, while the necessary level of J_{ex} is retained through tip weights – are not as high as those of the total blade mass (Figure (A.2). However, even the potential CF gains shown in Figure A.3 should have a noticeable influence on the loads transferred to the hub and hinges and thus, on the weight of that assembly as well.

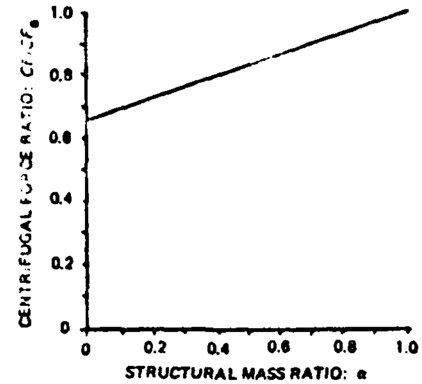


Figure A.3 Centrifugal force ratio, as α varies and f_{ex} = const

A.4 Coning Angle

Retention of the original (baseline) coning angle (a_0) should be considered as another strong constraint influencing the outcome of the total blade-weight reduction level that becomes potentially possible through the use of high-strength material

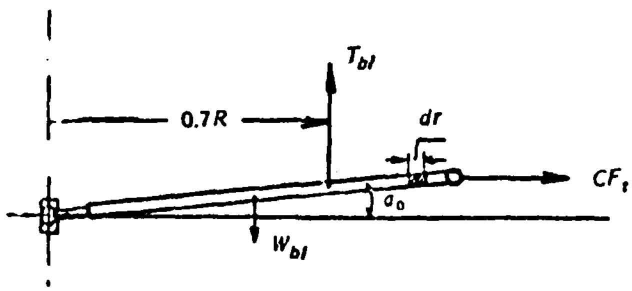


Figure A.4 Schematic of forces influencing the coning angle value

Conditions for the equilibrium of moments about the flapping hinge, when the coning angle is a_0, can be expressed as for the baseline blade with no tip weights (making small angle assumption and assuming that the flapping hinge is located on the rotor axis and that the resultant blade thrust is at $\bar{r}$ = 0.7, while the blade weight is at $\bar{r}$ = 0.5) as follows:

$$T_{bl}0.7R = \int_0^R \tilde{m}_0 r^2 \omega^2 a_0 dr + W_{bl}0.5R. \tag{A.10}$$

Neglecting the $W_{bl}0.5R$ product as being small in comparison with the centrifugal force term, and noting that the first term on the right side of Eq. (A.10) represents J_{ex} times a_0, the condition of the constancy of the coning angle can be expressed as

$$a_0 = 0.7RT_{bl}/J_{ex} = \text{const.} \tag{A.11}$$

But the $0.7RT_{bl}$ product is constant; hence, the requirement of maintaining a_0 = const is reduced to the J_{ex} = const condition. This obviously means that the blade weight aspects previously discussed in conjunction with the J_{ex} = const restraint also remain valid in the present case. Consequently, it may be assumed that Eq. (A.6), plotted in Figure A.2, should correctly express the potential overall weight reduction of the helicopter blade assembly when the weight of the blade core is reduced by the factor α.

A.5 Effect of J_{ex} and a_0 Constraints on Blade Weight Reduction

The following simplified case is considered in order to give the reader some idea regarding the influence of J_{ex} and a_0 constraints on the possibilities of blade weight reduction resulting from the application of advanced materials.

It will be assumed that both the baseline blade and the blade made of new materials consist entirely of load-carrying elements and, furthermore, that the dimensions of the elements are dictated exclusively by the allowable stress in bending. In this case, the expression in the square brackets in Eq. (2.41), giving the unconstrained ratio of the weight of the blade constructed of new materials to that of the baseline blade $(W_{bl_{nm}}/W_{bl_0})_{un}$, can be reduced to the following ratio of the weight-effectiveness indices.

$$(W_{bl_{nm}}/W_{bl_0})_{un} = \eta_{b_0}/\eta_{b_{nm}}. \tag{A.12}$$

This equation is graphically presented as a continuous line in Figure A.5.

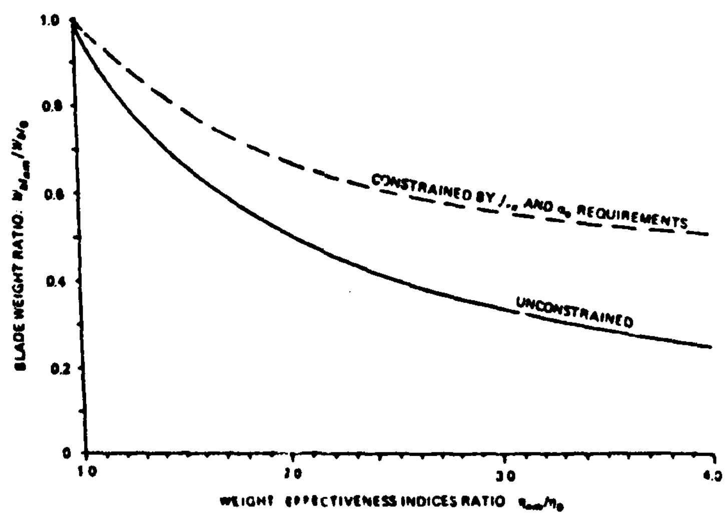


Figure A.5 Ideal blade weight ratio vs. weight effectiveness indices ratio of materials

The weight ratio expressed by Eq. A.12 may also be considered as the factor α, representing the weight ratio of the blade body incorporating new materials to that of the baseline blade

$$\alpha = \eta_{b_o}/\eta_{b_{nm}}. \tag{A.13}$$

When the moment of inertia and coning angle are retained, the total blade weight ratio will be obtained by substituting Eq. (A.13) into Eq. (A.6):

$$W_{bl_{nm}}/W_{bl_0} = 1/3 + (2/3)(\eta_{b_0}/\eta_{b_{nm}}). \tag{A.14}$$

The above expression is also plotted (broken line) in Figure A.5; thus, indicating the role of the J_{ex} and σ_0 constraints in restricting blade-weight reductions – potentially possible due to the improved specific weight-strength characteristics of new materials.

CHAPTER 3

ADVANCED STRUCTURAL MATERIALS AND CONSTRAINTS TO THEIR APPLICATION TO ROTORCRAFT

3.1 Introduction

In recent years, considerable progress has been made in the development of new structural materials, both metallic and nonmetallic, representing a high potential for reducing the relative weights of major rotorcraft components. These materials can be divided into three categories: (1) pure homogeneous metallic (steels and light alloys), (2) nonmetallic composites (usually based on high-strength fibers imbedded in resins), and (3) metallic-nonmetallic composites (combining, say, metallic elements with high-strength fibers through a resin-type connecting medium).

Although many of the new advanced structural materials represent a clear-cut advantage from the point of view of the weight of the rotorcraft component, application of these materials to practical designs encounter various constraints wich can be grouped into two classes: economic and operational. With respect to the first class, the cost of materials and manufacturing often represent a strong constraint. These aspects were discussed in detail by D'Ambra[8], Beziac[15], and in Ref. 16. Their inputs will be briefly reviewed in this chapter.

As far as operational constraints are concerned, the main reason for some of the hesitation or reluctance in wider application of composites is the lack of long-term experience with their behavior, especially crack propagation and delamination when exposed to various long-term climatic conditions, and other aspects of the operational environment.

Nevertheless, in spite of all of the above-mentioned constraints, there seems to be a growing trend toward an ever-increasing use of nonmetallic materials; especially composite materials, in the manufacture of major rotorcraft components. This point is well illustrated in Figure 3.1 (Figure 34, Ref. 15) representing some of the design philosophies of Aerospatiale. Figure 3.2 (Figure 3 of Ref. 8) is shown to give a more detailed example of this trend. In this exploded view of the Dauphin N1, the elements made of composite materials – constituting 19% of the weight-empty of 2038 kg (4493.8 lb) – can easily be determined.

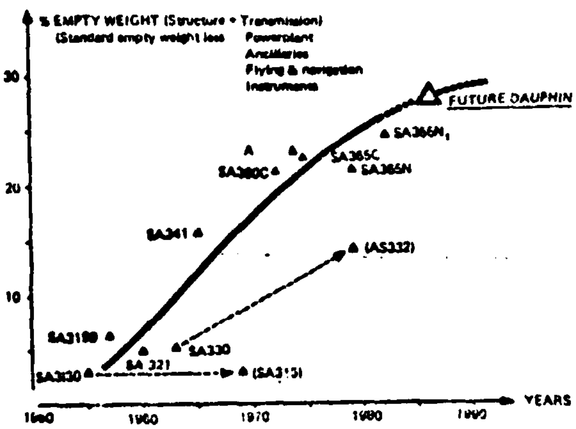


Figure 3.1 Past and future growth in application of composites to helicopters (Aerospatiale[15])

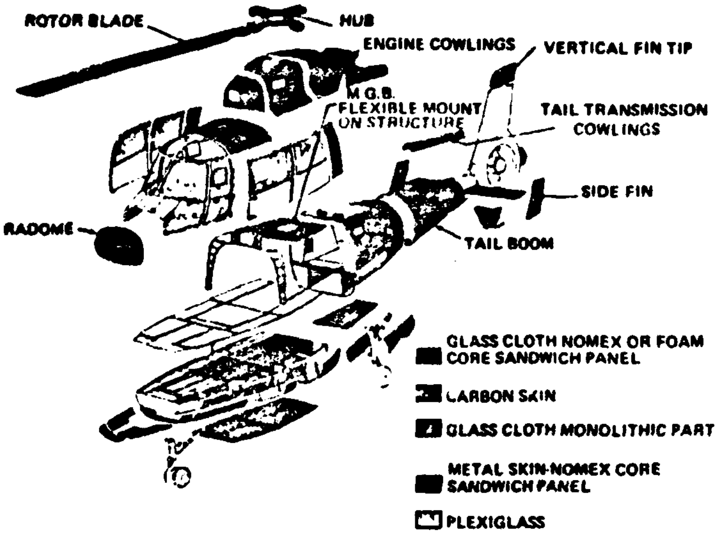


Figure 3.2 Exploded view of the Dauphin N1

However, five years later in the production version, the composite share should increase to 22% of W_e (see Table 3.1) and attain a value of about 30% by 1990 (Figure 3.1).

Table 3.1

Percentage of *various materials in the present* and future Dauphin structure

Material	EMPTY–WEIGHT PERCENTAGE	
	SA 365N1 Today	Future Dauphin
Light Alloys	34.5	32
Steel	31.0	30
Titanium	1.0	1
Composites	19.0	22
Miscellaneous	14.5	15
Weight Empty	2038 kg (4494 lb)	1950 kg (4300 lb)

In the U.S., there is also a strong increase in the use of composite structural materials in rotorcraft; especially in such new concepts as the tilt-rotor V-22 (Figure 3.3), where they may constitute as much as 31.5% of weight empty (Ref. 17). As stated in this reference,

> "Nearly all wing and fuselage structural elements are fabricated from graphite-epoxy composite laminates. This provides strength, stiffness, weight, and corrosion resistance.

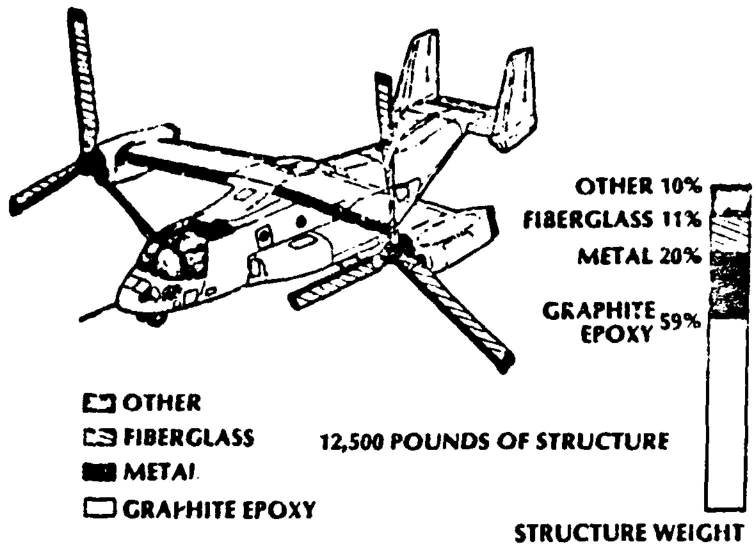


Figure 3.3 V-22 Material Applications

"Components, such as stiffeners, caps, and stringers, are structurally integrated by cocuring or cobonding them with the skin panels. This reduces the number of mechanical fasteners required in the structure.

"Composite structures weigh nearly 25 percent less than metal equivalents. Because approximately 60 percent of the Osprey will be fabricated of composites, considerable weight savings have been realized.

As far as helicopters are concerned, the composites used in the Boeing Vertol Model 360 constitute 60% of its weight empty, which probably represents the highest relative use of such materials. Here, combinations of glass and graphite are utilized in the blades, hubs, controls, rotor shafts, airframe, and landing-gear components (See Figure 3.4, Fig. 27 of Ref. 18).

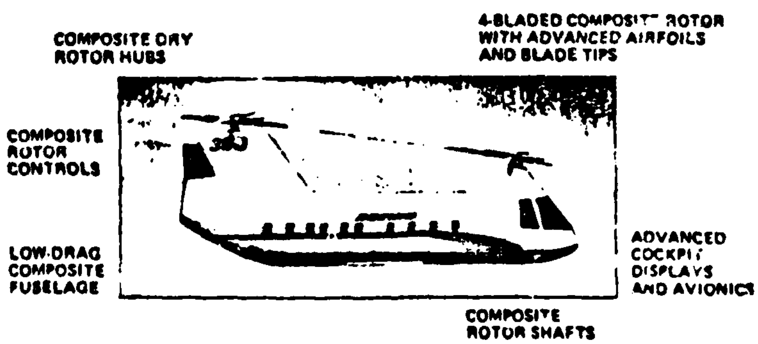
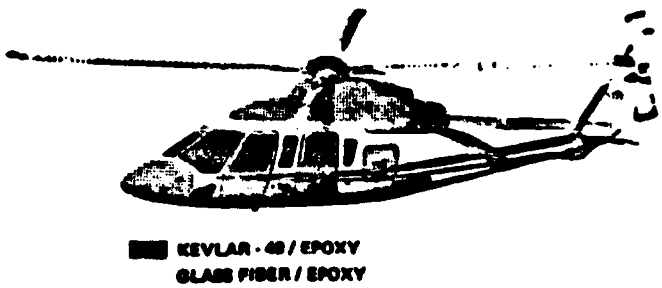


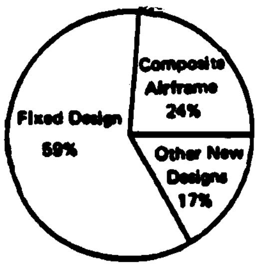
Figure 3.4 Model 360 Advanced Technology Helicopter

With respect to current U.S. production helicopters, the Sikorsky S 76 may be given as an example (Figure 3.5). This figures gives a general idea as to the use of composites ... and also the usage of various structural materials for the AC.



USE OF COMPOSITE MATERIALS ON THE S-76

DESIGN CATEGORIES ACAP WEIGHT EMPTY



	Lb	%
Composite Airframe	1433	24
Other New Design	1021	17
Fixed Design — (S-76, GFE, etc)	3539	59
Weight Empty	5993	100

MATERIALS USAGE — ACAP AIRFRAME

Material	Weight (Lb)	% WE
Composite	784.1	13.0
Aluminum	165.0	
Steel	79.9	
Fiberglass	27.8	
Glass & Plexiglass	75.5	
Miscellaneous	300.3	
TOTAL	1432.6	

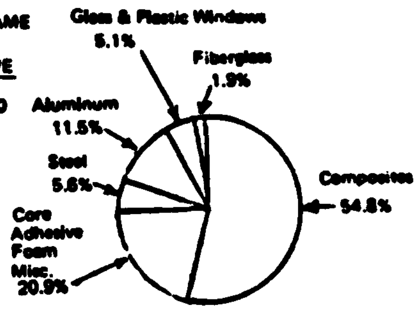


Figure 3.5 Use of composites in the S-76 and the ACAP

The trend toward a broader use of composites in helicopter structures is also depicted in the Soviet school of design. However, there is insufficient data available to this investigator to pinpoint definitive numbers to illustrate this trend. It would be desirable, hence, to make a separate study on this subject.

China is one of the countries having a potential for a large-scale rotary-wing industry that is also apparently getting involved in the application of composites. Here, as in other countries before them, the first application of composi s are directed toward main-rotor blades[19].

It is obvious that an indepth analysis into the many facets of advanced structural materials and their application to rotorcraft would exceed the order of magnitude of the intended scope of this study. Consequently, only certain aspects of the whole field of the application of advanced structural materials to major rotorcraft components are briefly reviewed in this chapteer, with the prime objective being to indicate possible trends and directions for a more thorough investigation.

3.2 Advanced Structural Materials

3.2.1 General

Although one usually associates the term "advanced structural materials" with composites either based on, or incorporating, high-strength fibers, it should not be overlooked that considerable progress has been, and is being, made in the improvement of homogeneous metals — especially, light alloys. In this respect, the aluminum-lithium alloys appear quite promising and, in particular, the fixed-wing industry both in the U.S. and Europe, seems to favor their application on a large scale. This position is motivated by the fact that replacing current aluminum alloys with new aluminum-lithium alloys can cut weight by 8% at a very small change in the overall cost[20] (also see Ref. 21). Composites are even more promising, offering the possibility of a 25% weight saving over metal construction for primary structures. But the previously mentioned constraint of cost, and uncertainties regarding operational aspects dictate a rather cautious approach regarding the use of composites to fixed-wing designers — especially those of commercial transports — in spite of the fact that the structural-weight reducing potential in fixed-wing aircraft has been demonstrated in many experimental aircraft, including the recent example of Rutan's Voyager (made almost exclusively of high-strength composites), where the relative weight-empty came down to approximately 16% of the maximum flying gross weight.

In contrast to the fixed-wing industry (especially that related to transport aircraft), rotary-wing designers appear willing to bypass the structural weight savings offered by advanced aluminum alloys and go directly to a broad application of advanced composite materials. An additional incentive for taking this approach is the possibility of creating components with optimal dynamic and, where applicable, aerodynamic characteristics. All-composite experimental main-rotor blades is a leading example for possible aerodynamic/dynamic optimization. It should be pointed out that experimental composite blades were developed as early as 1962, and improved versions have been used in U.S. production helicopters since the late 1970s.

3.2.2 Weight-Effectiveness Indices of Metals and Composites

Basic information required to determine weight-effectiveness indices for all kinds of structural materials is, unfortunately, dispersed through many uncoordinated publications. (The previously-referenced ANC-5 represents a good unified source of information regarding metals.) For this reason, summaries appearing from time to time in technical literature, covering a broad spectrum of structural materials, should prove to be of special value. "Materials Selector 1987" (Ref. 22) may be cited as one such useful publication. For example, Section A entitled, "Comparison of Materials" contains a summary of the following information of interest to students on the impact of advanced materials on the weights of rotorcraft components.

1. Density
2. Tensile yield strength
3. Ultimate tensile strength
4. Modules of elasticity in tension.

In addition to the above, this publication also contains weight-effectiveness indices expressed as strength, or modulus of elasticity-to-density ratios. Table 3.2 contains an excerpt from the original chart depicting absolute and specific strength of materials. Unfortunately, there is no data on fatigue strength in the summary tables, and little information in general about advanced composites being of special interest to rotorcraft designers.

TABLE 3.2

SPECIFIC STRENGTH OF MATERIALS, 10^3 IN.

The strength-weight ratio given in this table was determined by dividing the tensile yield strength or ultimate tensile strength by the density. Values for materials marked with an asterisk (*) were determined using ultimate yield strength. Tensile yield strength values were used for all others[22].

MATERIAL	HIGH	LOW
Graphite epoxy*	3509	–
Boron epoxy	2740	–
Polyesters, thermoset, pultrusions*	1428	345
Titanium & its alloys	1043	171
Stainless steels; standard martensitic grades; wrought, heat treated	982	214
Ultra-high strength steels; wrought, heat treated	931	616
Aluminum alloys, 7000 series	892	144
Cobalt & its alloys	879	89
Stainless steels; age hardenable; wrought, aged	826	380
Nickel & its alloys	689	35
Magnesium alloys; wrought	667	268
Carbon steels; wrought, normalized, quenched & tempered	664	206
Aluminum alloys, 2000 series	647	103
Vinylidene chloride copolymer, oriented*	635	246
Aluminum alloys, 5000 series	602	63
Alloy steels, cast; quenches & tempered	601	396
Ductile (nodular) irons, cast	584	160
Aluminum alloys, 6000 series	561	104
Aluminum casting alloys	539	86
Nickel base superalloys	534	143
Berylium & its alloys	533	75
Titanium carbide base cermets	516	130
Polycarbonate, 40 & 20% gl reinf*	511	372
Nylon, 30% gl rinf*	510	404
Stainless steels, standard austenitic grades; wrought, cold worked	483	272
Aluminum alloys, 4000 series	474	–
Polyester, thermoplastic, PET, 45 & 30% glass reinf	459	286
Magnesium & its alloys, cast	455	185
Tungsten	455	310
Iron base superalloys	445	140
Polyetherimide, 30% gl reinf	445	–
Copper casting alloys	433	33
Molybdenum & its alloys	423	226
Stainless steels, standard martensitic grades; wrought, annealed	376	89
Copper nickel, wrought*	372	137
Styrene acrylonitrile, 30% gl reinf.	367	–
Aluminum alloys, 3000 series	364	61
Bronzes, wrought	356	54
Rhenium	356	–
Columbium & its alloys	351	122
Cobalt base superalloys	348	117
High copper alloys, wrought	341	30
Polyetherimides, unreinf.	330	–
Polyester, thermoplastic, PBT, 40 & 15 glass reinf*	328	245
Plastic foams, rigid, internal skin, reinf*	323	115
Alloy steels, cast; normalized & tempered	322	134

To alleviate this situation, it would be desirable to generate summary tables of the most important material characteristics of interest to both rotorcraft designers and students of the weight aspects of rotorcraft components. An example of this approach is given in Table 3.3, where weight-effectiveness indices are given for some metallic and nonmetallic materials now being used or contemplated for new rotorcraft designs. It should be emphasized that Table 3.3 is only given here as an example. Actual working tables should cover a wider range of potentially useful structural materials and loading modes, which should further be supplemented by another table(s) containing information regarding non-load carrying materials. Finally, in order to retain the usefulness of such tables, they must be continuously updated.

The use of graphics is another way of presenting material characteristics in a manner which may be useful to rotorcraft designers and component weight watchers. The potential advantage of the graphical approach lies in that, in principle, one can, at a glance, roughly judge the competitive position of a given material. One drawback to this approach is that in order to generate a clear picture, only two characteristics can usually be coupled; for instance, weight effectiveness factors based on ultimate strength and those related to Euler's modulus of elasticity (Figure 3.6).

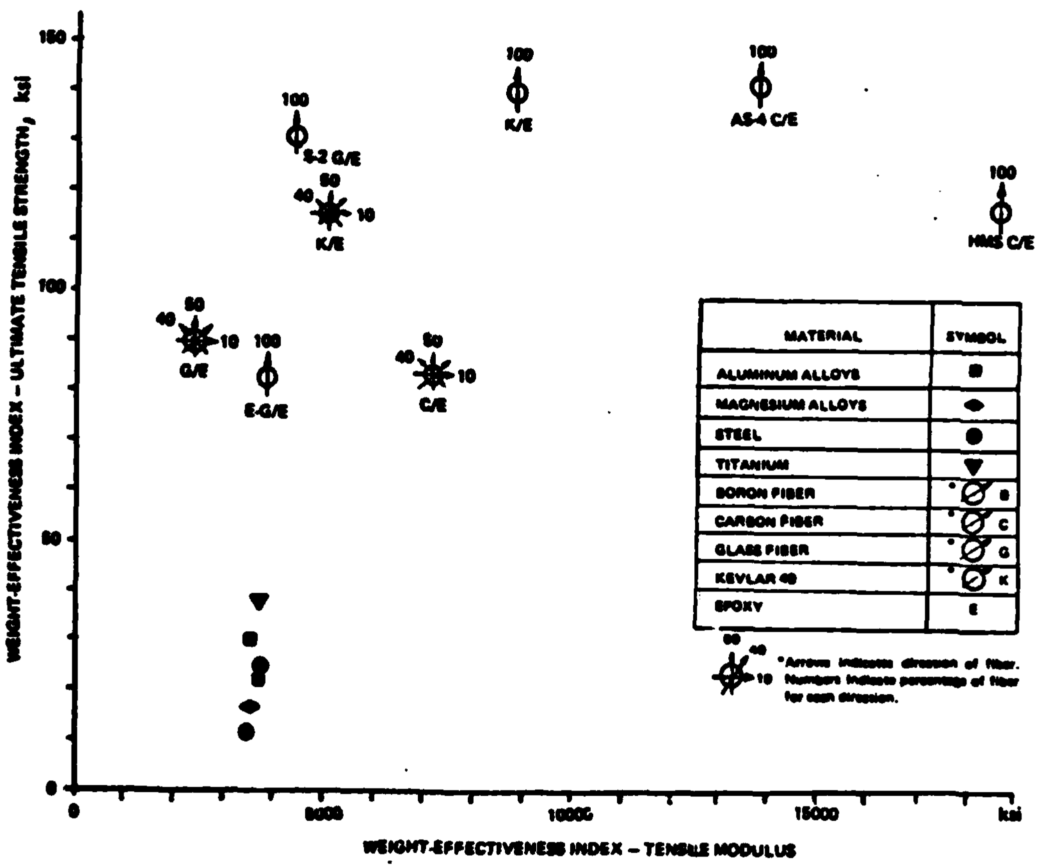


Figure 3.6 Weight-effectiveness indices based on ultimate tensile strength vs. tensile modulus of elasticity

TABLE 3.3

WEIGHT-EFFECTIVENESS INDICES OF PRINCIPAL STRUCTURAL MATERIALS FOR ROTORCRAFT

MATERIAL	SPECIFIC GRAVITY	WEIGHT-EFFECTIVENESS INDEX, ksi					
		STRENGTH				DEFLECTION	
		ULTIMATE TENSILE	ULTIMATE COMPRESS.	ULTIMATE SHEAR	ENDURANCE LIMIT	E	G
4130 STEEL (190 ksi UTS)	7.85	24.2	24.2	14.0(?)	11.5[1]; 6.1[3]	3,820	
TITANIUM 6AL 4VA	4.34	36.9	36.9			3,800	
ALUMINUM 7075-T6	2.71	30.6	30.6		6.7[3]	3,690	
CAST MAGNESIUM ZE63	1.87	22.6	36.7		9.8[4]		
GRAPHITE AS-4/E[5]	1.62	141.4	117.1		95.4	13,815	≈ 370
GRAPHITE HMS/E[5]	1.60	115.6	92.5			18,750	≈ 510
GRAPHITE HMS/E[6]	1.70	≈ 65				≈ 7,200	
KEVLAR 49/E[5]	1.36	139.7	30.9		96.6	8,823	≈ 242
KEVLAR 49/E[6]	1.44	115.3				5,075	
S-2 GLASS/E[5]	1.95	130.3	36.9		15.4	4,410	
E-GLASS/E[5]	1.95	82.1	36.4		5	3,897	

NOTES: [1]Reversed bending [2]Reversed torsion [3]$R = 0.1$; $N = 10^7$ [4]$R = -1.0$ (rotating bending); $N =$ [illegible] $\times 10^7$
[5]Unidirectional [6]Ply (50%, 0°; 40%, 45°; 10%, 90°) E – Epoxy

Figure 3.7 (based on Figure 6 of Ref. 15) shows an alternate method of pairing weight-effectiveness indices; namely, those related to the tensile modulus of elasticity vs. modulus of rigidity. This appears to be a good example of presenting the modulus of elasticity (E) vs. the modulus of rigidity (G) relationships for multilayer composites since, at a glance, one would see the effects of fibre orientation on the material weight-effectiveness characteristics when comparing the two types.

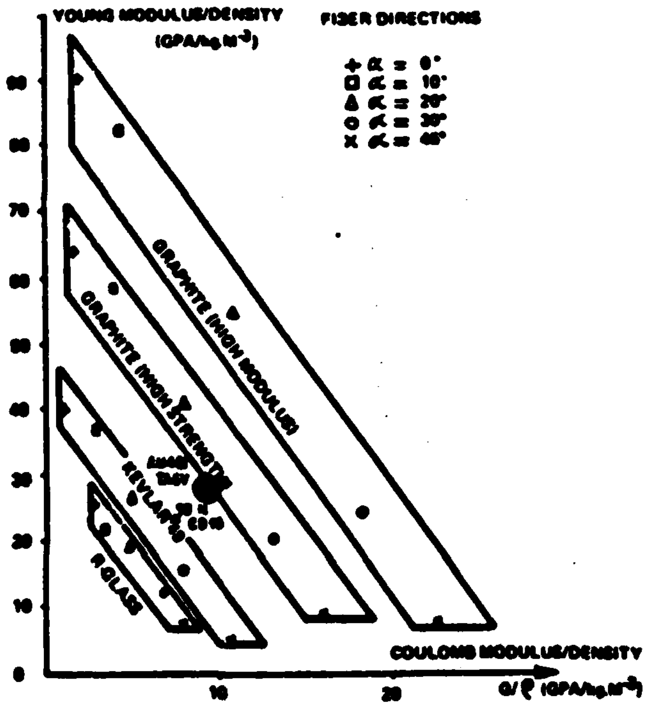


Figure 3.7 Effects of fibre orientation in composites of the E vs. G characteristics

Bar charts offer still another possibility for a graphic presentation of weight-effectiveness indices. Figure 3.8 is given as an example of this approach. Here, weight-effectiveness indices for each material are shown for ultimate strength and corresponding endurance limits, both in tension and compression. Indices in shear could probably still be added; thus providing easily depicted, rather complete information regarding weight reduction possibilities of the material. One disadvantage of this approach is that to avoid overcrowding, the number of materials that can be presented in one graph is limited.

Presenting a clear, easily understandable picture of material weight-effectiveness indices for fatigue conditions would prove to be a difficult task, even if only the most important aspects of the loading modes discussed in Section 2.4 were to be taken into account. Figure 3.9 (based on Herculed data) shows the weight-effectiveness indices for tension-tension cyclic tests at R = 0.1 conducted on a few composite and aluminum materials.

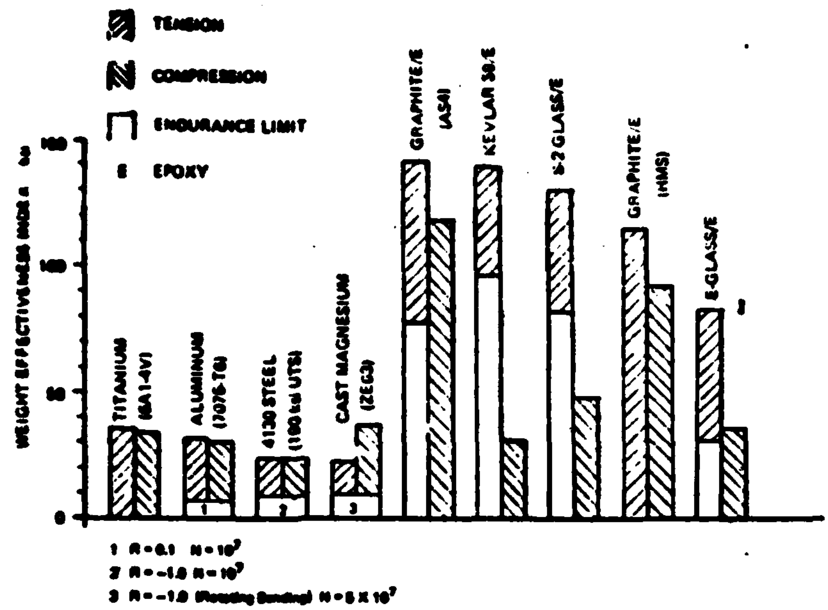


Figure 3.8 Example of bar-chart presentation of weight-effectiveness indices

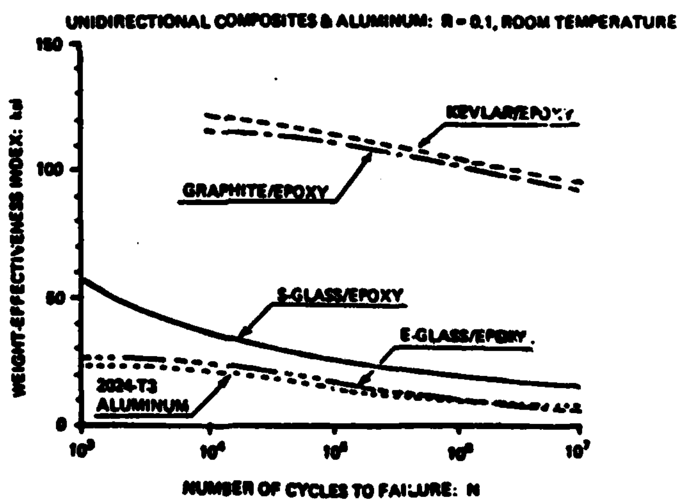


Figure 3.9 Weight-effectiveness indices for fatigueconditions

The whole review of weight-effectiveness aspects of structural materials suitable for rotorcraft seems to indicate that there is a need for establishing a unified source of information regarding properties of advanced, especially nonmetallic, materialsand developing a method of presenting the information in a concise manner for rotorcraft designers and to students of component weight trends.

3.3 Operational and Cost Constraints

3.3.1 General

The figures presented in the preceding section clearly indicate the potential of new structural materials — composites in particular — with respect to weight reduction of major rotorcraft components. In addition to the possibility of weight reduction, composites offer many other advantages from the design, military, civilian and, eventually, the manufacturing point of view. These non-weight aspects of the use of composites have recently been discussed in many papers and publications. However, they will not be reviewed here, as the present study deals almost exclusively with the influence of advanced material characteristics on the weight of rotorcraft components. Nevertheless, the reader's attention will be called to two constraints which, especially in the past, have had a negative effect on the broad use of nonmetallic composite materials in the pursuit of the goal of reducing the structural weight of the rotorcraft in addition to other inherent advantages. As with any other new developing technology, the main constraints appearing in this endeavor are (1) operational uncertainties, and (2) cost. Both are very briefly discussed below.

3.3.2 Operational Uncertainties

The lack of statistically significant experience regarding the behavior of composites under real-life operational conditions and suitable analysis methods generates a very strong reluctance on the part of potential users (both military and civilian) to accept rotorcraft having a large percentage of the load-carrying structure made of composites. Unfortunately, this creates the proverbial "the chicken and the egg" situation. Large-scale accelerated service tests probably represent one of the possible means of breaking that vicious circle. This may be helped by the fact that there are some major rotorcraft components; namely, the blades and, more recently, hubs, where real-life operational experience (generally favorable) has already risen to a significant level.

In some cases, the potential objections which the user may express are not to the composites per se, but to the particular structural solution. The unfavorable opinion of the Navy with respect to honeycomb structures because of potential damage of moisture accumulation can be cited as an example. There is also the uncertainty as to the influence of components made of composites on the structural integrity of the rotorcraft when exposed for an extended period of time to adverse climatic conditions; as well as to lubricants and other chemicals constantly present in the rotorcraft.

It is believed, however, that with the continuous, though slow, acquisition of actual operational experience, and development of more detailed specifications regarding the type of acceptable structures and exposure to chemicals, the reluctance of potential customers to accept rotorcraft using large amounts of composites for primary structures will decrease with time. Thus, operational uncertainties should cease to represent a strong constraint regarding the use of composites as a means of weight-saving for major rotorcraft components.

3.3.3 Cost

There are three major elements of cost which should be examined when utilization of new structural materials is being considered: (1) cost of the material, (2) cost of tooling and manufacturing facilities, and (3) cost of labor and energy (if significant) during the manufacturing process.

The cost of a new material when it appears on the market as a product ready for practical application is usually quite high; in many cases, several times more expensive than the material it is supposed to replace. However, the originally high material cost usually decreases with time; thus making it more and more economically acceptable or even more advantageous.

The graphite fiber price history (Hercules data) shown in Figure 3.10 well illustrates this point.

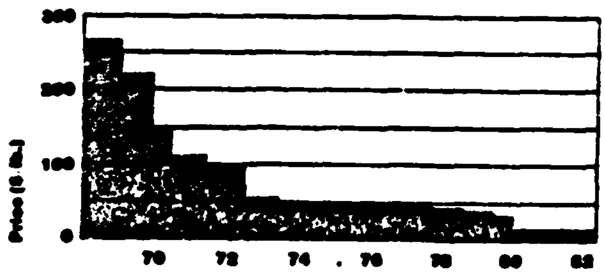


Figure 3.10 Graphite fiber price history

One can see from this figure that the price of graphite (expressed in actual dollars) has dropped very substantially in spite of the inflation in the late seventies, when the price of many other materials actually increased.

Other composite materials have followed the trend illustrated for graphite fiber. It may be anticipated that, in general, the cost of new advanced structural materials probably does not represent a strong constraint of limiting their application to rotorcraft components. However, a representative of the fixed-wing industry (Boeing) expressed a more conservative point of view (Ref. 20).

> "We will need the improved carbon fiber, with its higher strain and improved modulus, to make the expected gains over tried and true aluminum in primary structures. Improved fiber, we estimate, must be made for less than half today's price in order to achieve a cost-effective, all-composite primary structure."

The two cost constraints; namely, tooling and labor, are usually considered as an entity in a cost comparison of components manufactured from advanced materials vs. the baseline materials produced in a "traditional" manner. The reader may find summaries of such comparative studies in Refs. 8 and 15. Table 3.4 (based on a table from Ref. 15, but expressed here in dollars and U.S. measuring units) is given as an example.

At present, Aerospatiale is one company probably having the widest overall experience in dealing with various aspects of the application of composites to components of serially-produced helicopters. (US companies probably have more experience with composite blades, but not necessarily other components.) Consequently, the actual data and projections should correctly indicate the general trend regarding cost aspects.

In this respect, the message of Refs. 8 and 15 seems to be clear: in components such as blades, considerable cost reductions appear possible (Figure 3.11) although no weight-saving is anticipated (Figure 3.12), apparently because of the blade moment of inertia requirement.

TABLE 3.4

COMPARISON BETWEEN COST AND WEIGHT OF ISORIGID SANDWICH STRUCTURES WITH PANELS OF GLASS, GRAPHITE, OR KEVLAR WITH RESPECT TO LIGHT ALLOY SKIN PANELS (Aerospatiale, Ref. 15)

TYPE	SKIN PANELS		NOMEX® HONEYCOMB			ADHESIVE		TOTAL WEIGHT	TOTAL COST OF SANDWICH	ΔCOST/ΔWEIGHT RATIO	WEIGHT DIFFERENCE
	$\bar{w}$ lb/ft²	Cost \$/ft²	Thickness e in	$\bar{w}$ lb/ft²	Cost \$/ft²	$\bar{w}$ lb/ft²	Cost \$/ft²	lb/ft²	\$/ft²	\$/lb	Percent
Light Alloy e = 0.016 in.	0.460	1.25	0.39	0.184	4.05	0.116	2.7	0.696	8.1	0	0
E Glass 3-Ply Satin 8 e = 0.0116 in	0.630	2.80	0.51	0.133	5.28	---		0.782	7.88	−0.28	+12.6
Kevlar® 49 3 Ply Satin 8 e = 0.0116 in	0.480	8.28	0.43	0.113	4.45	---		0.602	12.72	+48.0	−13.8
Graphite T 300 1-Ply Satin 8 e = 0.016 3-Ply Satin 4 e = 0.020 in.	0.285	16.0	0.30	0.102	4.05	---		0.487	18.80	+9.3	−30.9

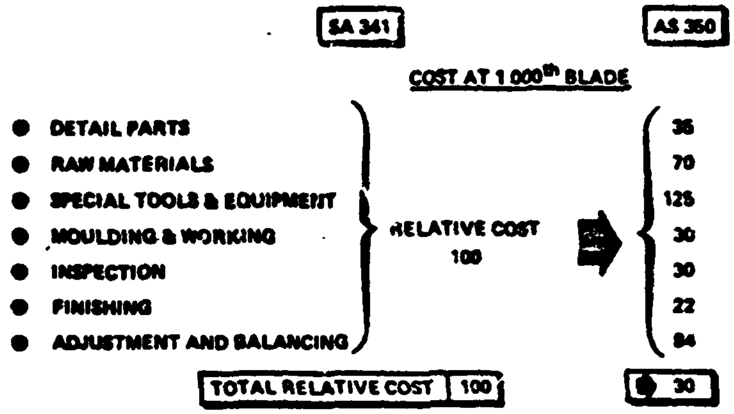


Figure 3.11 Reduction in production costs due to composite design

With respect to other components; for instance, rotor hubs, cowlings, tail booms, and empennage, both weight and cost savings are indicated (see Figure 3.12, reproduced from Ref. 5). It is obvious that significant weight savings have been achieved through new design solutions — made possible by special characteristics of the composites.

		WEIGHT SAVING (%)	CONVENTIONAL/MODERN COST RATIO
AS 350 / SA 341 ROTOR HUBS STARFLEX / NAT		42	2,7
AS 350 / SA 318 ROTOR BLADES COMPOSITE / METAL		~0	2,1
AS 350 / SA 316 FUEL TANKS ROTOMOULDED / METAL		− 6	12,7
SA 365 COWLINGS FOAM - GLASS / NOMEX - GLASS		20	1,5
SA 365 TAIL BOOM NOMEX-LIGHT ALLOY SANDWICH/ METAL		16	1,7
SA 365 STABILIZER CARBON TO METAL COMPARISON	TWO 1/2 STABILIZERS ON THROUGH-SPAR	40	0,9
	MONOBLOC THROUGH TAIL	50	1,30

Figure 3.12 Weight and cost advantages

In contrast to the Aerospatiale attitude, opinions expressed by representatives of fixed-wing transports (Boeing) appear much more conservative (Ref. 20).

> "Advanced composites show great promise for major primary structures. Designers anticipate weight savings of 25% over metal construction. ...However, here cost plays an important role. A 767 rudder made of carbon-fiber composite costs almost exactly the same as one made of aluminum but weighs less and is a good buy. The labor was less for composite but the material much more expensive. But in the case of 757 trailing-edge flaps, both material and labor for a composite version were more expensive."

The above statement, as well as future goals of Boeing regarding cost are depicted in Figure 3.13.

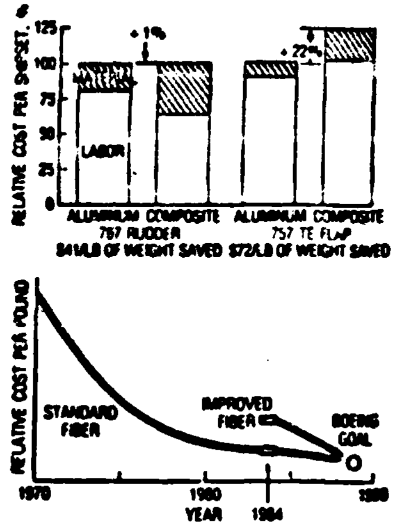


Figure 3. Actual Boeing experience in application of composites and projection for the future

After weighing the opinions expressed by both rotorcraft and fixed-wing industries, one is inclined to state that, in general, cost would not present a strong constraint regarding the application of composite materials to roto . t components.

CHAPTER 4

CONCLUDING REMARKS

4.1 General Conclusions

The insights gained through performance of this study lead to the following conclusions:

- Investigation of the historic trends in relative weight empty ($\overline{W}_e$) of helicopters coupled with studies of the effect of aircraft size (expressed through maximum flying gross weight) indicated a rapid decline in $\overline{W}_e$ values through the fifties for all gross-weight classes of Western and Soviet designs. This was followed by a much slower decrease in $\overline{W}_e$ levels from the sixties up to the present. Relative empty weights of the existing tilt-rotor (XV-15) in the STOL and, especially, VTOL, operational modes, are well above the corresponding helicopter levels. $\overline{W}_e$ values projected for future tilt-rotor designs (designated as the V-22 in the U.S., and EUROFAR in Europe) are still above those of their helicopter counterparts.

- The rapid decline in helicopter $\overline{W}_e$ values during the fifties and early sixties was, to a large extent, due to the transition from reciprocating to gas-turbine type power-plants, as this change reduced the relative engine weight levels from about 9.5% for helicopters of the early fifties to about 3.5% for contemporary models. This may lead one to conclude that further improvements in the specific weights of power-plants would exert little influence on $\overline{W}_e$ values. However, for new rotorcraft concepts — which would be expected to have a lower power loading than corresponding helicopters — the influence of relative powerplant weights on $\overline{W}_e$ levels could, again, be quite significant.

- Since the relative empty weights of rotorcraft are, in turn, the result of the relative weights of their major components, graphs showing historic and size-related trends in $\overline{W}_e$ along with those of the relative weights of components and their optimal boundaries should provide a clear and comprehensive insight into the process of achieving certain $\overline{W}_e$ levels. Such graphs would prove especially useful for concept-formulators and designers of helicopters and new rotorcraft concepts by providing them with a basis for making realistic weight assumptions for new designs and provide standards for assessing the weight-effectiveness of the aircraft as a whole, as well as individual components, once the detailed designs are completed or even after the objects of the assessment are actually built. However, in order to retain their usefulness, such trend-graphs must be kept continuously updated.

- Although somewhat slower than before the early sixties, the steady decline in $\overline{W}_e$ helicopter values must obviously be attributed to a general lowering of the relative-weight values of components (excluding those of engines). However, one may expect that the rate of decline may not be the same for all components. For example, temporal relative weight trends of lifting rotor blades for Western helicopters show only a slight decline in $\overline{W}_{bl}$ with time. (At first, Soviet $\overline{W}_{bl}$ values declined rapidly, but gradually leveled off.) These, almost constant, relative weights of lifting blades can be attributed to strong constraints resulting from the requirements of certain values for the blade moment of inertia. However, some reductions in $\bar{W}_{bl}$ (through application of highly weight-effective structural materials) appear theoretically possible (see Appendix to Chapter 2).

- The decline in relative weights of major helicopter components is chiefly due to the application of new structural materials, exhibiting higher and higher strength as well as elongation and rigidity moduli to specific weight ratios (indicated here as material weight-effectiveness indices). Knowledge of the weight-effectiveness indices for materials used in the baseline component and those in a new design, should enable one to, at least roughly, estimate the relative weight ratios of the new to the original components. However, in this process, weight-effectiveness indices should be determined with due consideration of the loading conditions of various elements, taking into account such factors as number of loading cycles during the anticipated operational life of the component, loading modes (R values), and state of the surface.

- Weight-effectiveness indices point toward wider and wider application of composites as structural materials in rotorcraft. Initially, the high cost of composites, together with limited operational experience in their use, appeared as strong constraints to their implementation. But price declines resulting from constantly increasing sales volume and labor-saving manufacturing techniques have improved the cost aspects. Generally favorable feedbacks from operators regarding the behavior of composites in the field has lowered the resistance of designers toward the use of these materials. Consequently, one may now observe a definite trend toward a wider acceptance of nonmetallic materials in helicopter structures. In new rotorcraft concepts, such as tilt-rotor or the X-wings, the use of composites has become a 'must' in order to achieve the $\bar{W}_e$ levels necessary for competition with conventional helicopters, especially in VTOL-type operations.

4.2 Recommendations

Because of the limited scope of this study, several factors affecting past, present and, possibly, future trends in the relative weight-empty of rotorcraft and other VTOL configurations had to be omitted, in spite of the fact that the importance of these factors has been indicated by the work already performed. To rectify this situation, the following additional efforts are recommended:

- Perform a study of trends — both historic and size-related — of specific weights and specific fuel consumption of Western and Soviet powerplants that are applicable to rotorcraft and other VTOL configurations. Then, evaluate the impact of these trends on the relative weight empty levels of rotary-wing and other VTOL concepts, as well as on fuel requirements per unit of aircraft gross weight, unit of distance traveled, and unit of time on station.

- Expand and refine mathematical expressions and computational procedures for predicting the influence of new structural materials on the weight of major rotorcraft components in comparison with the baseline weights. The so-established methods should then be tested by making comparisons of predicted and actual weights of components manufactured from advanced materials.

- Assemble up-to-date data on advanced structural materials already on the market and those expected to become available in the future (say, up to 5 years). Then, upon establishing the most suitable and comprehensive way of presenting weight-effectiveness indices of materials, prepare a practical means of making that information available to the aircraft technical community.

REFERENCES

1. Stepniewski, W.Z. and R.A. Shinn. "A Comparative Study of Soviet vs. Western Helicopters: Part 2 – Evaluation of Weight, Maintainability, and Design Aspects of Major Components." NASA CR 3580, AVRADCOM TR 82-A-10, March 1983.

2. "Jane's All the World's Aircraft." London. 1955/56 through 1986/87.

3. Andres, J., H. Hubner, and J. Renaud. "The Tilt Rotor Aircraft: Response to the Future?" From European Interrogations to EUROFAR Actions. Paper presented at the Twelfth European Rotorcraft Forum, Garmisch-Portenkirden, W. Germany. Sept 22-25, 1986.

4. Tishchenko, M.N., A.V. Nekrasov, and A.S. Radin. "Viertolety, vybor parametrov pri proektirovaniy: Helicopters, Selection of Design Parameters." Mashinostroyeniye Press, Moscow. 1976.

5. Stepniewski, W.Z. "A Comparative Study of Soviet vs. Western Helicopters, Part 1 – General Comparison of Designs." NASA CR 3579, AVRADCOM TR 82-A-9. March 1983.

6. Faust, H. and J. Mack. "Composite Applications in the Drive System." Paper presented at the 42nd AHS Forum, 1986.

7. Lenski, J.W., Jr. "Development of Graphite/Polyimide Composite Transmission Housing." Journal of the AHS, Vol. 30, No. 2, pp. 24-31. April 1985.

8. D'Ambra, F. "The Impact of New Materials on the Development of Rotary Wing Aircraft." A.N.I. Aerospatiale. Marignane, France.

9. O'Brien, T.K. "Generic Aspects of Delamination in Fatigue of Composite Materials." Journal of the American Helicopter Society, Vol. 32, No. 1, pp. 13-18. January 1987.

10. Albrecht, C. "Statistical Evaluation of a Limited Number of Fatigue Test Specimens Including a Factor of Safety Approach." Symposium on Fatigue Test of Aircraft Structures." ASTM STP No. 338. 1962.

11. Albrecht, C. "Generalized S-N Curve Shapes – Steady Stress Effects." Journal of the American Helicopter Society, Vol. 32, No. 1, pp. 26-32. January 1987.

12. MIL-HDBK-5D. "Metallic Materials and Elements for Aerospace Vehicle Structures." Vol. 1. June 1983.

13. Thompson, G.H. "Boeing Vertol Fatigue Life Methodology." Presented at the AHS Specialist Meeting on Helicopter Fatigue Methodology, St. Louis, Mo. March 1980.

14. Edwards, P.R. "A Description of HELIX and FELIX, Standard Fatigue Loading Sequences for Helicopters, and of Related Fatigue Tests Used to Assess Them." Ninth European Rotorcraft Forum, Stresa, Italy. Sept. 1983.

15. Beziac, Gilbert. "Applications of Composite Materials in Helicopter Fabrication." Aerospatiale Helicopter Division.

16. AVRADCOM/NASA. "Technology Assessment of Capability for Advanced Joint Vertical Lift Aircraft (JVX)." Summary Report, Analysis & Preparation chaired by AVRADCOM. May 1983.

17. Anon. "The V-22 Osprey Overview." Brochure by Bell-Boeing, the Tilt-Rotor Team.

18. Shaw, J., L. Dadone and R. Wiesner. "Rotorcraft Technology at Boeing Vertol; Recent Advances." Presentation given at 1987 NASA/Army Rotorcraft Technology Conference, Moffett Field, Ca. March 17-19, 1987.

19. Chenglin, Zhang and Xiaogu Zhang. "Design and Development of a Composite Main Rotor Blade for the Y-2 Helicopter." Ninth European Rotorcraft Forum, Paper No. 47, Stresa, Italy. Sept. 13-15, 1983.

20. Swihart, J.M. "Which Transport Technologies Will Fly?" Aerospace America, Vol. 24, No. 5, May 1986.

21. Pope, G.G. "Structural Materials in Aeronautics: Prospects and Perspectives." Aerospace, Parts 1 & 2, Vol. 13, Nos. 4 & 5, April & May/June, 1986.

22. Anon. "Material Selector 1987." Comparison of Materials, Dec. 1986.

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Variation in the weight of rotorcraft and their major components due to the use of advanced materials ~~is the topic of this study~~. The impact of new materials on component weights is illustrated by historical weight trends. The influence of structural material characteristic on the relative weight levels of major rotorcraft components, the weight effectiveness, for both static and fatigue-type loadings are reviewed. Cursory expressions are developed to permit estimation of how the strength effectiveness values or structural materials affect the relative weights of components. Special constraints which could limit the possible weight reductions achievable are considered briefly. A survey of advanced structural materials is also included.

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